GEOLOGICAL SURVEY OF WESTERN AUSTRALIA

MINERAL RESOURCES BULLETIN 14

NICKEL MINERALIZATION

IN

WESTERN AUSTRALIA

1984

NICKEL MINERALIZATION IN WESTERN AUSTRALIA

An oblique aerial view, from the south-southwest, of the Kambalda nickel deposits. In the foreground is a grid of causeways on Lake Lefroy. Diamond drilling from these causeways has been used to define the broad extent of the Lunnon and Hunt shoots which plunge south-southeast under the lake. In the middleground the township of Kambalda East nestles in hills of the metabasalt which underlies the ore-bearing ultramafic formation. The concentrating plant lies just north of the township. Kalgoorlie-Boulder is just below the horizon, right of centre. Photograph taken on 23 November 1978 and reproduced by permission of the Surveyor General, Western Australia.

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NICKEL MINERALIZATION

IN

WESTERN AUSTRALIA

by

R. J. MARSTON

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PREFACE

Western Australia currently provides about 7 per cent of the world's mine production of nickel (1978). It is the third largest producer of sulphide nickel, supplying some 12 per cent of mine production, and possessing nearly 15 per cent of the total identified resources of nickel in sulphidic ores containing 0.8 per cent or more nickel. The State's rise to this significant position began only in 1966, with the discovery of the Kambalda deposits. Exploration reached a peak in 1969-70 during the notorious "nickel boom", a significant episode in the history of the Western Australian mineral industry. The expenditure of some $200 million from 1966 to 1976 led to the discovery of about 100 million tonnes of high-grade (2.3% Ni) mineralization, almost entirely confined to the eastern part of the Archaean Yilgarn Block. The resultant mining has been followed by locally established smelting and refining operations.

The author's study of the State's nickel mineralization and resources involved field inspections of all important deposits and most of the remainder, as well as petrographic and mineragraphic laboratory work. He combined his own data with information already published, and with material supplied to the Geological Survey by mining companies, to give an account of each deposit and its geological setting. Deposits are initially divided into sulphidic and lateritic, and the former are subdivided into five types.

The work on which this bulletin is based was carried out between 1977 and 1979. To facilitate early appearance of some general conclusions from this study, Dr Marston's joint authorship of a review paper* published in 1981 in Economic Geology was given approval. However, most of the information in this bulletin is now made available for the first time, and it should provide the first and most essential reference for anyone interested in exploring for nickel in this State for many years to come.

A. F. Trendall,
Director Geological Survey

* Marston, R.J., Groves, D.I., Hudson, D.R., and Ross, J.R., 1981, Nickel sulfide deposits in Western Australia: A review. Economic Geology, v.76 (6), pp.1330-1363.

CONTENTS

CHAPTER 4 INTRUSIVE DUNITE-ASSOCIATED DEPOSITS

CHAPTER 5 VOLCANIC PERIDOTITE-ASSOCIATED DEPOSITS

CHAPTER 6 GABBROID-ASSOCIATED DEPOSITS

CHAPTER 7 LAYERED SEDIMENTARY-ASSOCIATED DEPOSITS

CHAPTER 8 VEIN-TYPE AURIFEROUS-ARSENICAL DEPOSITS

CHAPTER 9 OTHER NICKEL SULPHIDE DEPOSITS

CHAPTER 10 LATERITIC DEPOSITS

CHAPTER 11 RESOURCE POTENTIAL

APPENDICES

PLATES

FIGURES

TABLES

SUMMARY

Nickel is a bright, white metal which resists corrosion and finds its major use in the production of stainless steel. Western Australia supplies about 7% of the world's mine production of nickel from mines developed in the Eastern Goldfields region since 1966. Annual state mine production since 1975 has been about 55 000 tonnes of contained nickel with mining, smelting and refining operations being dominated by Western Mining Corporation Ltd. Copper, cobalt, platinum-group metals and gold are important by-products.

Ultramafic igneous rocks rich in olivine or its altered equivalents have the highest contents of nickel present in both silicate and sulphide minerals. Nickeliferous minerals occur in (1) sulphide deposits of nickel, iron and copper sulphides at depth, or their weathered equivalents at (gossans) or near the surface, and (2) in lateritic deposits of silicates and oxides in laterite and weathered ultramafic rock.

Nickel sulphide deposits have mainly been found in the eastern half of the Yilgarn Block. A few sulphide deposits are known from the Pilbara Block, Halls Creek Province, Albany-Fraser Province and the Musgrave Block. Lateritic nickel deposits are known only from the Yilgarn and Musgrave Blocks, but exploration for such deposits has been limited compared with the intense exploration for sulphide deposits. Based primarily on the nature of the host rock, sulphide deposits are classified into five types:

1. *intrusive dunite-associated deposits (e.g. Agnew, Mount Keith)*
2. *volcanic peridotite-associated deposits (e.g. Kambalda, Nepean)*
3. *gabbroid-associated deposits (e.g. Carr Boyd Rocks, Sally Malay)*
4. *layered sedimentary-associated deposits (e.g. Sherlock Bay)*
5. *vein-type arsenical deposits (e.g. Mount Martin)*

Some 96 per cent of the sulphide nickel metal resource is contained in intrusive dunite-associated and volcanic peridotite-associated deposits concentrated in the curvilinear, folded and strike-faulted supracrustal belts of the eastern Yilgarn Block. Very magnesian ultramafic rocks and laminated sulphidic metasediments abound in these belts, which have commonly been metamorphosed to greenschist or lower amphibolite facies conditions. Major strike faults probably influenced the nature and distribution of volcanism and sedimentation, and later tectonometamorphic styles. The faults also had a role in controlling nickel mineralization.

Intrusive dunite-associated deposits occur in semi-concordant lenses of peridotite to olivinite composition and of komatiitic affinities, which are restricted to curvilinear zones 100 km or more long. Coarse polygonal olivine with interstitial chromite and sulphides forms the olivinite, but rounded olivine with interstitial pyroxene, sulphide and oxide phases characterizes the peridotite. These rocks are variously metamorphosed to assemblages of olivine, serpentine, brucite, pyroaurite-group minerals, talc, magnesite and anthophyllite, plus opaque phases. Nickel sulphides occur centrally or marginally in the thickest part of the lens. Low grade (<1 per cent Ni) sulphides are voluminous and enclose smaller bodies of higher grade disseminated and massive or breccia ores, which may be partly tectonically displaced. The nickel content of the sulphide faction is about 10% (although low grade sulphides may be Ni-rich) with ranges of Ni:Cu of 19 to 70 and Ni:Co of 30 to 70. The lenses may have been emplaced (i) passively as subvolcanic sills which fractionated olivine and sulphides and gave rise to associated komatiitic lavas; and/or (ii) dynamically as dyke-like bodies of sulphidic olivine-rich crystal mush.

Volcanic peridotite-associated deposits are best developed at or near the base of volcanic komatiitic ultramafics occurring between metabasalts, and at low stratigraphic levels in the succession. There is little or no geographical coincidence between these deposits and the intrusive dunite-associated deposits. The ultramafics are mainly lavas ranging from picrite to olivine peridotite in composition, but thicker and more magnesian flows dominate the lower, mineralized part of the pile, where thin interflow sulphidic metasediments are also common. In a typical mineralized flow a thick zone of granular olivine with interstitial pyroxene, sulphides, oxides and glass was overlain by a thin zone of spinifex-textured olivine and pyroxene plus glass, now converted to assemblages of antigorite, chlorite, tremolite, talc, magnesite and dolomite plus opaque phases. About 90 per cent of the mineralization is at the base of the lowermost olivine peridotite unit in the ultramafic pile. The mineralized flows appear to be tongue-shaped and to occupy original depressions in basalt surfaces devoid of sulphidic sediment. Thin, discontinuous massive sulphides resting on metabasalt are overlain by thicker, continuous and more extensive matrix to disseminated sulphides. Some massive and breccia ores are tectonically displaced. The nickel content of the sulphide fraction varies from 5 to 23 per cent with an accompanying increase in Ni:Cu from 10 to 16 and Ni:Co from 40 to 65. On eruption of sulphidic komatiitic magma sulphide segregation under differential flow and gravity would probably result in the observed cross-section through ore, but with subsequent physical modification of the ore during metamorphism.

Gabbroid-associated deposits occur in layered or composite intrusions of gabbronorite with lesser pyroxenite, peridotite and anorthosite, which crystallized from basaltic magma of uncertain affinity. The rocks are incompletely hydrated. Low grade disseminated or blebby sulphides from layers or irregular bodies associated with lenses or veins of matrix, massive or breccia sulphides. Intercumulus sulphide textures are preserved in some matrix to disseminated ores. The nickel content of the sulphide fraction is up to about 6 per cent, with Ni:Cu of 1 to 7 and Ni:Co of about 25. The bulk chemistry of the intrusions and the sulphides and sulphide-silicate textures are consistent with the existence of immiscible sulphide liquids at the magmatic stage.

Layered sedimentary-associated deposits are small and occur in bedded metasedimentary rocks, rich in calcium, iron and magnesium, which are found in mafic-ultramafic and mafic-felsic volcanic sequences. Disseminated to matrix sulphides form thin stratiform layers which have a nickel content of the sulphide fraction of less than 10 per cent. Only three deposits are recognized: these have a range of Ni:Cu of 5 to 17. The nature of these deposits suggest a volcanic-exhalative origin.

Vein-type arsenical deposits are also small and rare, and all are associated with gold mineralization. Most deposits consist of disseminations and veinlets of quartz, carbonates, sulphides and arsenides in or near carbonated ultramafic rocks. The deposits are probably of late metamorphic-hydrothermal origin.

Lateritic nickel deposits have formed by the deep weathering and ferruginization of olivine-rich ultramafic rocks which are generally devoid of sulphides. Average nickel contents are typically 1.2 to 1.4 per cent accompanied by minor, but in places commercially important, amounts of cobalt. Discontinuities in bedrock structure may give rise to deeper weathering and/or restricted groundwater flow and thereby produce higher nickel or cobalt contents than the average.

The identified nickel resources of Western Australia with a bulk grade of more than 1 per cent nickel are (1) 123.6 million tonnes averaging 2.10 per cent nickel for sulphide deposits and (b) 355.9 million tonnes averaging 1.03 per cent nickel for lateritic deposits. Most known deposits are in the eastern Yilgarn Block but as no more than a fifth of this area forms outcrop, many more deposits should remain to be discovered beneath the mantle of superficial deposits. New exploration methods will be needed as most sulphide deposits have been discovered by the recognition of siliceous limonitic cappings of gossans at the surface.

CHAPTER 1

Introduction

CONSTRUCTION OF BULLETIN

OBJECT AND SCOPE

This bulletin reports the results of a study of nickel mineralization in Western Australia undertaken by the writer in the period October 1977 to December 1979. The object of the study is to summarize available geological information and to assess, where possible, the resources of all important deposits in which nickel is the metal of major commercial interest.

The bulletin is not concerned with deposits of other metals in which nickel is present in uneconomic amounts. Many nickel deposits contain economically recoverable amounts of copper, cobalt and precious metals. Deposits with Ni:Cu less than 1.0 in average grades are generally not dealt with, but reference may be made to Marston (1979). Occurrences of cobalt and platinum-group metals are included only if they accompany nickel.

SOURCES OF INFORMATION

The information presented has been compiled from published sources, unpublished reports of mining companies and tertiary institutions, Mines Department and Geological Survey files, plans held by the Drafting and Geological Survey Branches of the Mines Department, petrological studies and from field inspections made in 1978 and 1979.

LAYOUT

The first two chapters of the bulletin provide general and historical information, discuss the petrology of ultramafic rocks, and describe the characteristics of nickel as a component of the earth's crust. Chapter 3 sets the scene for the bulk of the remaining bulletin by (i) describing the tectonic provinces of the State which contain nickel mineralization; and (ii) defining the major types of deposit found therein. Descriptive and measurable features are used to classify deposits into types. Chapters follow which describe each group of deposits falling into a specific type. A summary of the geology, mineralization and inferred genesis of the deposit type prefaces each of these chapters. Chapter 11 deals with exploration methods and their effectiveness, and goes on to consider the potential for further discoveries, based upon these factors and their cost, and inferred regional controls of nickel mineralization.

TERMINOLOGY AND ABBREVIATIONS

For usage in this bulletin the definitions of the terms *stratabound, stratiform, syngenetic, diagenetic, epigenetic,* hydrothermal, hypogene, supergene resource, ore, reserve (and qualifying terms), deposits, occurrence, prospect and mine are followed as set out in Marston (1979). The petrological nomenclature of ultramafic rocks is discussed in Chapter 2.

Further terms requiring definition are given below. The following three adjectives describe sulphide abundances in rocks: (i) *disseminated* sulphides make up less than 40 per cent by volume of the total rock; (ii) *matrix* sulphides account for between 40 and 80 per cent; whereas (iii) *massive* sulphides constitute at least 80 per cent of the rock volume. The minerals accompanying the sulphides are generally referred to as *gangue;* they are commonly of no commercial value.

A *gossan* is the oxidized and leached outcrop of an ore—gangue mineral assemblage, which contained sulphides, sulphosalts, carbonates or oxides. Commonly the gossan will exhibit limonite boxwork textures after the sulphides, and some of the oxides and gangue minerals. A *pseudogossan* is an ironstone outcrop, with or without cellular texture, which has developed over barren rock. It commonly contains abundant transported (exotic) limonite.

Laterite is used to refer to soils, sediments and weathered rock rich in iron oxides, calcium-magnesium carbonates, secondary silica and clay minerals, which overlie and generally pass down into fresh ultramafic rock. Laterite is commonly indurated.

The use of hyphens and plus signs in assemblages of mineral names has the following significance: a hyphenated series, e.g. talc-chlorite-amphibole, means that the minerals are present in roughly equal proportions. Minerals preceded by a plus sign are present in lesser amounts, e.g. talc-chlorite + amphibole + carbonate, amphibole and carbonate are subordinate to talc and chlorite. A combined ± sign indicates that the mineral following is present in some rocks but not in others.

Abbreviations used which require definition are listed below.

t	tonnes
m.y.	million years
M	million
GML	gold mining lease
mss	monosulphide solid solution
MC	mineral claim
ML	mineral lease
TR	temporary reserve
Sheet	1:250 000 series map area
BIF	banded iron-formation

A list of abbreviated mining company names follows:

Abminco	Abminco N.L.
ACM	Australian Consolidated Minerals N.L.
Acmex	Acmex Holdings N.L.
Ada	Ada Exploration
Allstate	Allstate Explorations N.L.
Amad	Amad N.L.
Amax	Amax Exploration Australia Inc. formerly Amax Mining Australia Inc.
AMC	Agnew Mining Company Ltd
Amoco	Amoco Minerals Australia Co.
Anaconda	Anaconda Australia Inc.
Anglo American	Australian Anglo American Services Ltd formerly Anglo American Corporation Ltd
Anglo-Westralian	Anglo-Westralian Mining Pty Ltd
Aquitaine	Aquitaine Australia Minerals Pty Ltd
Asarco	Asarco (Aust.) Pty Ltd
Australian Ores & Minerals	Australian Ores & Minerals Pty Ltd
BHP	The Broken Hill Proprietary Co. Ltd
BMC	Amalgamet Australia Ltd formerly British Metal Corporation
Carpentaria	Carpentaria Exploration Company Pty Ltd
Carr Boyd	Carr Boyd Minerals Ltd
Central Norseman	Central Norseman Minerals N.L.
Charterhall	Charterhall Mining Exploration Pty Ltd
Cliffs	Cliffs International, Inc.
Conwest	Conwest Exploration (Australia) N.L.
CRA	Conzinc Riotinto of Australia Exploration Pty Ltd
Delhi	Delhi International Oil Corporation
Eastmet	Eastmet Minerals N.L.
Endeavour	Endeavour Oil Company N.L.
Esso	Esso Australia Ltd
EZ	Electrolytic Zinc Company of Australasia Ltd
Falconbridge	Falconbridge Nickel Mines Limited
Freeport	Freeport of Australia Inc.
Geometals	Geometals N.L.
Glomex	Glomex Mines N.L.
Gold Fields	Consolidated Gold Fields Australia Ltd
Great Boulder	Great Boulder Mines Ltd
Greenbushes Tin	Greenbushes Tin N.L.
Group Explorations	Group Explorations Pty Ltd
Hawkstone	Hawkstone Investments Ltd formerly Hawkstone Minerals
Hollandia	Hollandia Ravensthorpe N.L.
INAL	International Nickel Australia Ltd
INCO	International Nickel Company of Canada, Limited
Jododex	Jododex Australia Pty Ltd
Kennco	Kennco Explortions (Australia) Pty Ltd formerly Kennecott Explorations (Australia Pty Ltd)

Kingsway	Kingsway Minerals N.L.
Kralco	Kralco Mineral Corporation Pty Ltd
Laporte	Laporte Australia (Holdings) Ltd
Le Nickel	Le Nickel (Australia) Exploration Pty Ltd
MCE	Mining Corporation Exploration N.L.
Metals Ex	Metals Exploration Ltd
Minefields	Minefields Exploration N.L.
Minimp (ICI)	Minimp Pty Ltd
NBHC	New Broken Hill Consolidated Ltd
Newmont	Newmont Pty Ltd
NGM	Norseman Gold Mines N.L.
N. Kalgurli	North Kalgurli Mines Ltd
Otter	Otter Exploration N.L.
Outokumpu	Outokumpu Oy
Peko	Peko-Wallsend Ltd
Placer	Placer Prospecting Pty Ltd
Planet	Planet Management and Research Pty Ltd
PMI	Pickands Mather and Co. International
Poseidon	Poseidon Limited N.L.
Project Mining	Project Mining Corporation Ltd
Richenda	Richenda Minerals N.L.
Roebourne Exploration	Roebourne Exploration and Mining Ltd
Selcast	Selcast Exploration Ltd
Selco	Australian Selection (Proprietary) Ltd
Shell	Shell Company of Australia Limited
Shell Minerals	Shell Minerals Exploration (Australia) Pty Ltd
Sherritt Gordon	Sherritt Gordon Mines Limited
Serem	Serem (Australia) Pty Ltd
SLN	Societe Anonyme Le Nickel
Spargos	Spargos Exploration N.L.
Sumitomo	Sumitomo Shoji (Australia) Pty Limited
Tanks	Tanganyika Holdings Ltd
Tasminex	Tasminex N.L.
Texasgulf	Texasgulf Australia Ltd
Tin Creek Mining	Tin Creek Mining Corp
Unimin	Union Miniere Development and Mining Corporation Ltd
Union Oil-Hanna-Homestake	Union Oil Development Corporation — Hanna Limited — Homestake Iron Ore Company of Australia Ltd
Utah	Utah Development Co.
Vam	Vam Limited
Westfield	Westfield Minerals (W.A.) N.L.
Westralian Nickel	Westralian Nickel Exploration N.L.
Whim Creek	Whim Creek Consolidated N.L.
WMC	Western Mining Corporation Ltd
Woodsreef	Woodsreef Mines Limited
W. Selcast	Western Selcast Pty Ltd

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NICKEL IN THE WORLD'S ECONOMY

PROPERTIES AND USE OF NICKEL

Pure nickel is a bright, white, metallic element, which is the third member of a triad with iron and cobalt in the periodic table. Like these metals, it is magnetic. Nickel has a specific gravity of 8.92 g/cm^3, a melting point of 1453°C and a low coefficient of thermal expansion. The ability of the metal to resist corrosion, and to impart corrosion resistance, strength, hardness and other physical properties to alloys results in a wide usage in industrial and consumer goods. About 95 per cent of nickel produced is used in this way. There are more than 3 000 alloys containing nickel, but stainless steel, typically containing about 8 per cent nickel, is the commonest nickel-bearing product. Chemical uses of nickel or its compounds in alkaline batteries, dyes, ceramic coatings, pigments, insecticides, or as a catalyst, are minor by comparison. However, the current development of a commercial nickel-zinc battery for electric vehicles represents an enormous potential demand for the metal.

The chemical and petroleum refining industries use large amounts of corrosion-resistant stainless, alloy, and heat-resistant steels which contain more than 8 per cent nickel. High-nickel alloys are used for anti-caustic or saline corrosion applications. Monel metal (67 per cent nickel, 28 per cent copper, plus iron, manganese, silicon and carbon) is a highly corrosion-resistant alloy used in shipbuilding, food processing equipment, hospitals and laundries. Stainless steel used for cutlery, kitchenware, tools and general hardware is familiar to all. Cast and wrought nickeliferous alloy steels are widely used in machinery to provide strength. Nickel in the alloy also improves the response to heat-treating and machining. Certain nickel alloys with high tensile and creep strengths above 980°C are known as superalloys. As a strategic metal nickel is important in steels used for amour plate, gun forgings, shells and bullets. Being corrosion resistant also, such alloys are important ingredients of aircraft engines and frames. Electroplated parts of aircraft, motor vehicles and household goods all contain nickel. The electrical industry employs resistance-alloys of nickel (up to 80 per cent) and chromium in heating elements. Kovar, an alloy of nickel, iron and cobalt, has a similar coefficient of thermal expansion to glass, which allows gastight glass-metal seals to be made for electrical equipment. Nickel is used in coinage as a silver substitute.

Substitution for nickel as a component in alloys and special steels is not widespread because this often involves either an increased cost, or some loss in the desired properties of the end product. However, replacement of corrosion-resistant nickeliferous metals by plastic or plastic-coated steel, and alternative finishes (paint, enamel, polished aluminium) to nickel-chrome electroplating are important fields for substitution.

PRODUCTION

Nickel gained its name from the nickel arsenide niccolite, formerly known as "kupfernickel", a mineral which spoilt some otherwise valuable copper (kupfer) ores or was mistakenly thought to be copper ore, and was therefore associated with the misdemeanours of the devil or "old Nick". The first reference in print to kupfernickel by that name was by Hjarne (1694) in Sweden, though German miners referred to it as "Kupper Nicell" as early as 1654 (Howard-White, 1963). The same country in 1751 was the scene of the first isolation of nickel metal by Axel Cronstedt, who was working on cobalt ores, some of which contained gersdorffite, another nickel arsenide. Cronstedt named the new metal "nickel" in 1754, after what at that time appeared to be its chief ore.

In Europe a use for nickel was not found until about 1823, when an alloy of nickel, copper and zinc proved to be suitable for tableware. A similar alloy was previously known to the ancient Chinese, but in Europe it was called "German silver" and later "nickel silver". The previously discarded nickel-rich portions of cobalt ores mined in Germany were treated to provide this nickel. Mining of nickel ore did not begin in earnest until the 1840s when it took place in France, Germany and Scandinavia. Gabbro-associated sulphide desposits in Norway were the largest producers. Small deposits in Greece, Italy, Sweden, the USSR and the United States of America were also worked intermittently in the mid-19th century, but it was the discovery in 1863 by Jules Garnier of nickel silicate ("garnierite") lateritic ores in New Caledonia that presaged an era of large-scale nickel production. By the time of Garnier's discovery the use of nickel had increased, with applications in electroplating and coinage attaching more importance to the metal. Mining of small, but rich fissure deposits of garnierite in New Caledonia began in 1875, and a nickel smelter was built at the capital Noumea in 1877.

The district that became the world's principal single source of nickel was discovered at Sudbury, Canada, in 1856. One of several samples taken by geologist Alexander Murray from a gossan-stained ridge assayed 2 per cent copper and 1 per cent nickel. At that time the area was too remote and the find was forgotten. Mineralized outcrops in the area were accidentally found in 1883, during construction of the Canadian Pacific Railway, and the resulting intensive exploration led in 1886 to the re-discovery of the gossan-stained ridge. This ridge proved to be the hanging wall of the Creighton ore body (Boldt and Queneau, 1967). Canada replaced New Caledonia as the world's largest nickel producer in 1905, and first place has since been retained by that country. The largest producing company in Canada is INCO, whose operations are based at Sudbury.

Overall, world mine production of nickel has increased exponentially this century (Fig. 1). Large surges in production stemmed from increased strategic demands during both world wars. During the second world war two major new sources of nickel came into production. Lateritic deposits at Nicaro, Cuba were brought into production in 1943, using United States capital, and by 1945 New Caledonia was displaced by Cuba as second largest producer. All Cuban production was nationalized by the Castro government in 1960. In 1942 in what was then Finland, the Petsamo mine, previously developed by INCO, was put into production under German control. The USSR annexed this part of Finland (Kola Peninsula) in 1944 and

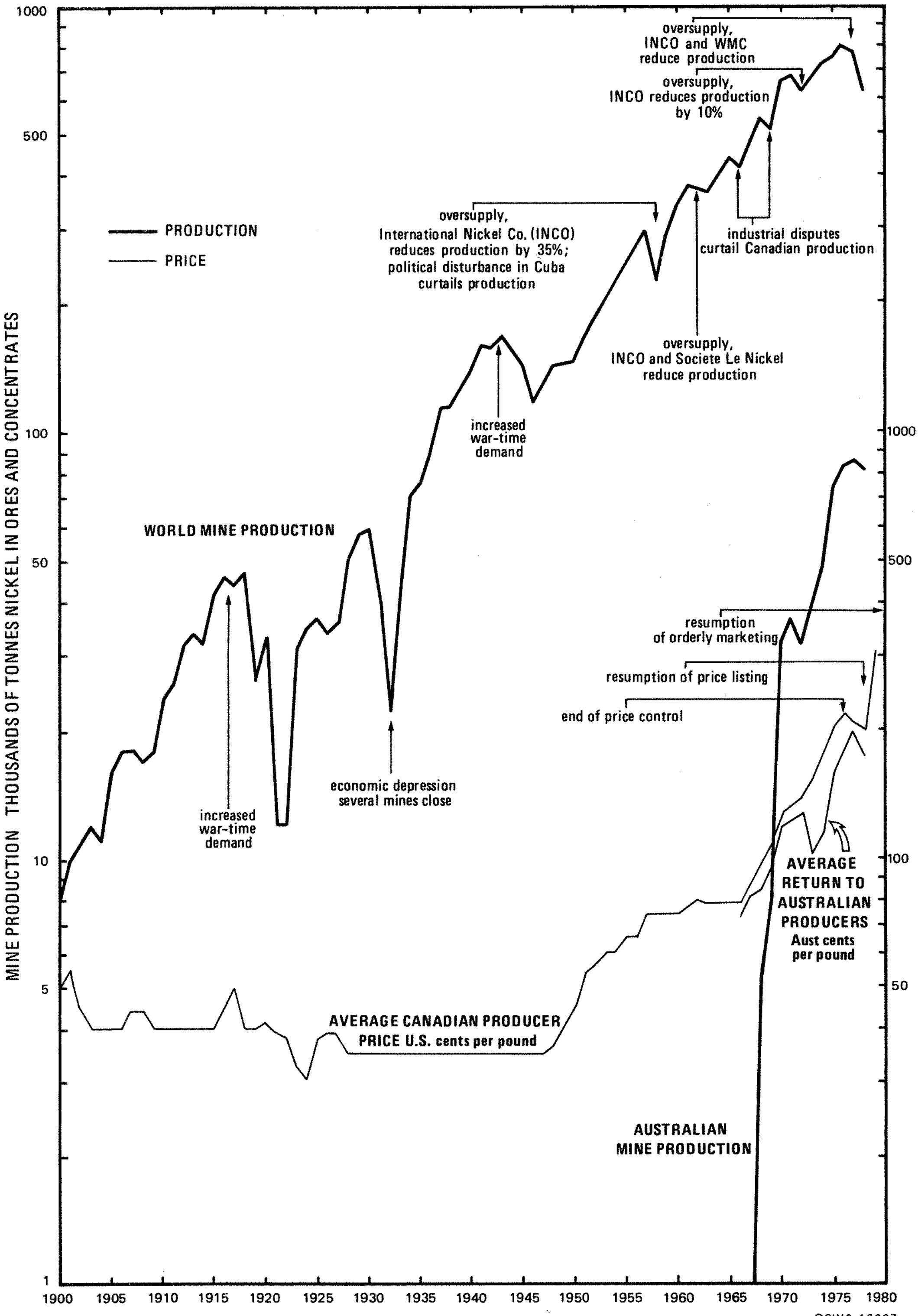

Figure 1. World and Australian mine production of nickel, average Canadian producer price, and average return to Australian producers, 1900-1979.

changed the mining district's name to Pechenga. In 1947 Pechenga was the third largest World producer of nickel, and since then the mines in the Kola Peninsula together with the Noril'sk district in Siberia have supplied the bulk of the Soviet Union's nickel requirements.

Following a brief lull after the second World war, the trend of exponential production growth resumed. Nickel production in New Caledonia from 1951 to 1960 was triple that in the previous decade. A new mine opened by Sherritt Gordon (Canada's third largest producer) at Lynn Lake in Manitoba made important contributions to production increases in Canada. An oversupply resulted and INCO reduced production in 1957. Further imbalances in supply and demand have affected the industry from time to time ever since (Fig. 1).

In the 1960s INCO opened more mines at Sudbury and two mines in the newly discovered Thompson district, Manitoba. The second largest Canadian producer, Falconbridge, also undertook a major operational expansion in Canada (based on Sudbury). Both these companies have invested heavily in large lateritic nickel mining projects outside North America. A Falconbridge subsidiary operates the Falcondo ferronickel project in the Dominican Republic: full output commenced in 1973. A major share is held by INCO in lateritic projects in Guatemala and Indonesia, with mining at both beginning in 1976.

Excepting a few thousand tonnes of nickel ore produced intermittently from 1913 to 1938 in Tasmania, nickel production in Australia can be regarded as dating from March 1967 when the first Kambalda deposit came into production. At present, Australia supplies about 11 per cent of world mine production, which gives the nation fourth ranking after Canada (about 32 per cent of world production), the USSR (about 20 per cent) and New Caledonia (about 15 per cent). Other important producers now are Cuba (about 5 per cent), the Dominican Republic (about 3 per cent), South Africa (about 3 per cent as by-product of platinum mining), the Philippines (about 2 per cent), Greece (about 2 per cent), Indonesia and Rhodesia. The United States, Japan and Western Europe are major importers of nickel and ferronickel.

The latest round of mine production cutbacks came in late 1977, in the face of the lowest demand for nickel by the non-communist countries since 1972. Annual production in the near future in Australia will probably remain at 80 000 to 85 000 tonnes of contained nickel. Western Australia provides about 66 per cent of this figure (Fig. 2). Large-scale production from the lateritic deposits at Greenvale, Queensland began in August 1974. Greenvale is the only Australian producer outside Western Australia.

MARKETS AND PRICES

Until recently the price of nickel (in $US per pound of cathode nickel, greater than 99.9 per cent purity, f.o.b. producer's warehouse) was set by the World's largest producer, INCO. In general, the other large producers, Falconbridge and SLN, have closely co-operated with INCO in maintaining a producer price for nickel. A small amount of nickel was sold on the free market at the free market price.

Before 1950 the nickel price remained relatively constant (Fig.1), even during the economic depression of the thirties because of control of sales and stocks by the major producers. Prices were raised by some 20 cents in the early 1950s to enable producers to mine lower grade ore, and to exploit the lateritic nickel deposits on a large scale. In the period 1954-1967 the price was steady in "real-value" terms, as rising quoted prices were more or less equivalent to the rate of monetary inflation.

This stability ended in 1966, when all three of the major Canadian producers were crippled by strikes. Demand exceeded supply despite the availability of large stocks, and the free market price of nickel rose to twice the producer price. The Canadian producer price set off on an exponential rise, given further impetus by another labour dispute in 1969 (Fig. 1), when the free market price reached a peak value of seven times the producer price. This prompted Sherritt Gordon to announce that in future their products would be sold at the free market price, as the company did not regard itself as a major producer. The state of the nickel market in the period 1966 to 1970 was ideal for bringing the newly discovered deposits in Western Australia into production, and the well-known "nickel boom" resulted.

The average Canadian producer price has risen steadily since 1970, but because of adverse exchange rates between Australian and United States currencies in the period December 1972 to August 1975, the Australian producers (who sell at the ruling $US producer price) were severely disadvantaged (Fig. 1.). Unity in the timing of price changes by INCO, Falconbridge and SLN broke down in 1974, partly because the latter two companies felt higher cost pressures from the increased price of oil used in their (high energy-consuming) lateritic ore smelters. Price increases announced by INCO in late 1975 and October 1976 were not applied until several months afterwards in both cases, because of fierce competition for sales in the light of weak demand (1975 economic recession) and large stocks. Discounts, allowances and special concessions were widely employed by producers in the 1976 market, and INCO eventually formalized reality in July 1977 by rescinding its price increases of October 1976, and stating that what it charged buyers would in future be considered "confidential business information". The Canadian share of the non-communist World's nickel production had declined from 65 per cent in 1966 to 38 per cent in 1976, thus preventing INCO from continuing its concept of stable producer prices based on production cost rather than demand. The newer producers came from less developed countries, and an aggressive marketing policy had been adopted by them.

By the end of 1977 the situation had become critical. Stocks of unsold nickel held by INCO alone amounted to 154 000 t, nearly twice the annual Australian production. Falconbridge, SLN and WMC also held abnormally large stocks. Production cuts were clearly long overdue, and prices were at a low of around US$1.80 per pound. In December, 1977 a return to listed prices was initiated by Amax. This company, having acquired minority interests in nickel ore producers in Botswana and New Caledonia, became a secondary producer in 1971 with the purchase of the Port nickel refinery in Louisiana (idle since Freeport's mining complex at Moa Bay in Cuba was seized in 1960).

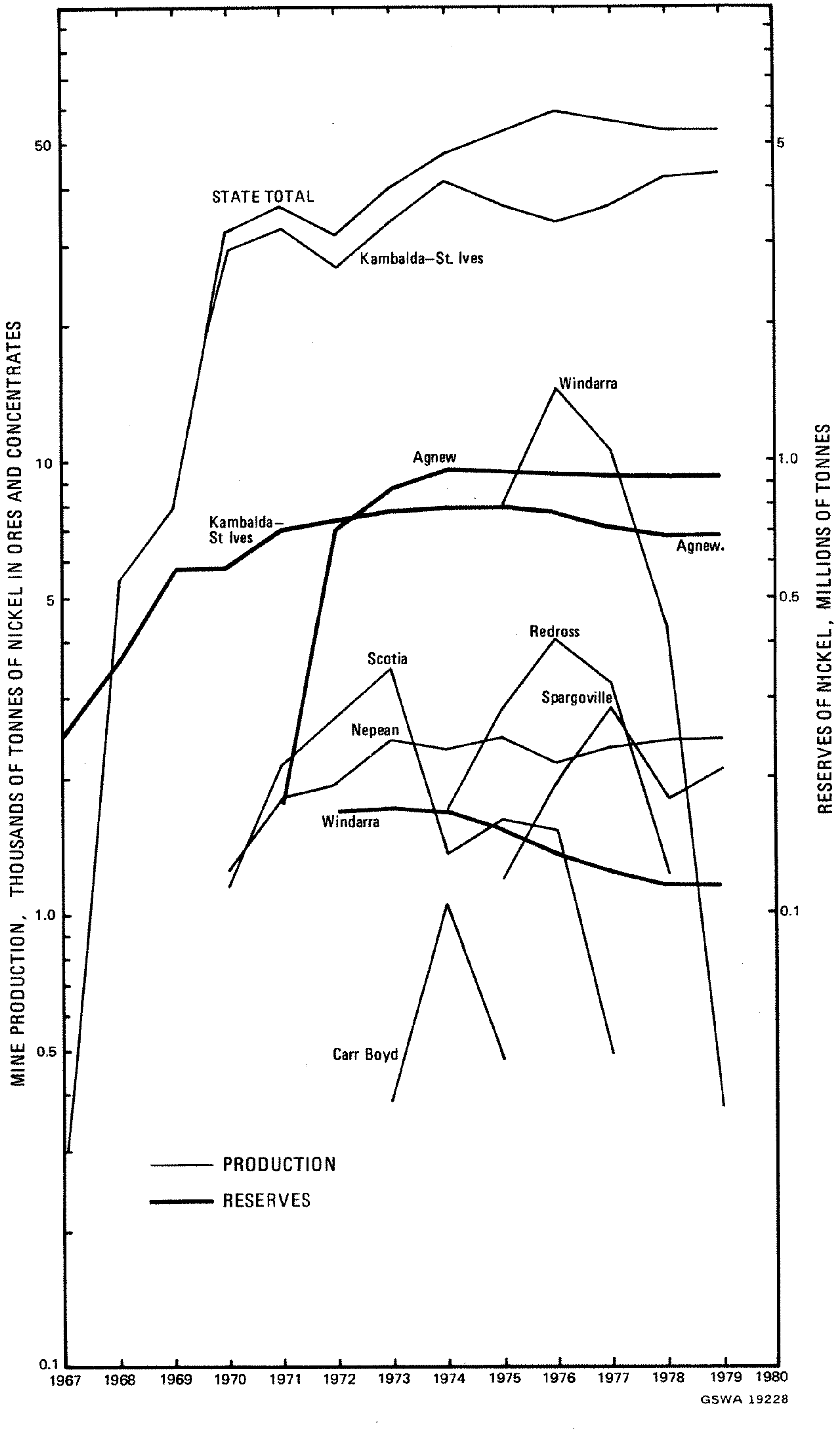

Figure 2. Mine production of nickel and major ore reserves, Western Australia 1967-1980.

In the first half of 1978 the producer price stabilized at around US$2.00 per pound, and most large producers achieved a substantial cut-back in production, helped in INCO's case by labour strikes. Price cutting returned to the market in August, and the free market price remained below US$1.85. The prospect of demand and supply achieving a lasting balance seems unlikely, even through the 1980s, unless the growth rate in consumption exceeds the expected range of 3.5 to 5.0 per cent per annum. Growth in production capacity is mainly the preserve of lateritic nickel projects in the southwest Pacific, Guatemala, Cuba and Greece. Consumption of ferronickel (20 to 30 per cent nickel), the chief end-product of smelting lateritic nickel ores, has risen sharply in recent times because of the development of the argon-oxygen decarburising vessel for stainless steel making. The development of the lateritic nickel projects, which will soon dominate World nickel production, can be seen as a response to changing market demand and declining sulphide ore resources. However, the lateritic nickel producers face severe problems in maintaining profitability in the light of large cost increases in oil. Ferronickel production needs 60 to 90 per cent more energy than nickel extracted from sulphide ores. The new sulphuric acid leaching process developed by Amax shows considerable promise as it can deal with oxide and silicate ore and achieves an energy saving of some 40 per cent.

With declining stocks caused by a protracted labour dispute, INCO resumed the practice of posting list prices in February 1979, when US$2.10 per pound was being asked by producers for cathode nickel. At the end of 1979 the market was in approximate balance and stocks had returned to normal levels.

Trading of nickel on the London Metal Exchange began in mid-1979. In mid-1980 prices were a little above the US$3 per pound mark for electrolytically refined nickel.

COBALT AND PLATINUM-GROUP METALS

Cobalt and platinum-group metals are minor by-products of the treatment of nickel ores, but their importance to producers has recently increased because of marked price increases. The chief uses of cobalt are in high-temperature alloys and superalloys (e.g. gas turbine and jet engines), magnetic alloys (electrical and electronic applications), chemicals (especially catalysts in hydrocarbon refining), machine tools and as the metal matrix for tungsten carbide in cutting tools. Platinum-group metals are mainly used in jewellery, as catalysts in petroleum refining (high-octane fuels), and in catalytic converters in automobile exhaust systems. The metals have high melting points and good resistance to corrosion, which makes them suitable for many sundry applications in the chemical and electrical industries.

Cobalt occurs in extractable amounts in both sulphide and lateritic ores, but platinum-group metals are of sufficient abundance only in sulphide ores. Nickel-sulphide ores have Ni:Co ratios of 20 to 60, whereas in lateritic ores the ratio is commonly between 10 and 15. Recovery of cobalt tends to be higher from lateritic and pyrrhotitic sulphide ores compared with pyritic sulphide ores. This is because much of the cobalt is within pyrite, and most of the pyrite goes into the tailings during milling. Copper-cobalt deposits in Zaire have supplied the bulk of the World's cobalt.

Platinum-group metals occur in very small amounts (hundreds to a few thousand parts per billion) in sulphide ores. Platinum and palladium are the most abundant of these metals. Metal contents tend to be greater in ores associated with differentiated ultramafic-mafic intrusions, with exceptionally high concentrations recorded from the Merensky Reef (Bushveldt complex, South Africa) and Noril'sk (West Siberia). These two areas account for about 90 per cent of the World production of platinum-group metals.

Until recently the price of cobalt has remained stable (in terms of constant dollars), the actual price increasing from US$1.50 to US$4.00 per pound in the period 1961 to 1976. The 1976 civil war in Angola prevented the export of Zaire's production via the Benguela railway, causing prices to rise above the US$5.00 mark. A more serious disruption to supply occurred in 1978 because of guerilla activity in Shaba Province, the chief producing district in Zaire. The producer price of US$6.40 per pound posted in February had escalated to $18.00 by September, and the free market price was over $30.00 in that month. Currently (1980) the producer price stands at $25.00. This imbalance in supply and demand is expected to be temporary, unless a major political realignment takes place in Zaire. The proportionally increasing nickel production from the lateritic deposits will contribute more cobalt to the market in the 1980s. Commercial exploitation of cobalt-nickel-copper-bearing manganese nodules on the ocean floors is another possible source in the future.

In terms of constant dollars, the producer prices of platinum (controlled by South African producers) and palladium (controlled by the USSR) have been reasonably stable in the past, until the late 1970s. Platinum prices were about US$160.00 per troy ounce in the mid-1970s, but rose to artificially high levels of around US$300.00 (higher on the free market) in late 1978 when the United States dollar declined to abnormally low values on money markets. Like other precious metals, platinum-group metals have become susceptible to speculative buying pressures in recent times. The producer price for platinum at the end of 1979 was US$380.00 per ounce.

NICKEL MINING IN WESTERN AUSTRALIA

HISTORY AND PRODUCTION

The presence of nickel-bearing minerals in gold-bearing veins in the Eastern Goldfields had been noted as early as 1897, but not until the early 1950s were nickel deposits sought in the State. Lateritic ochreous nickel deposits were discovered in 1953 in the Wingelinna area of the Blackstone region, near the Western Australia — South Australia — Northern Territory border junction (Fig. 3). Several prospecting teams went to the area, including one sent by WMC. South Western Mining Ltd (a subsidiary of INCO) investigated the deposits from 1955 to 1970. Mineable resources were estimated in 1972 (by Nickel Mines of

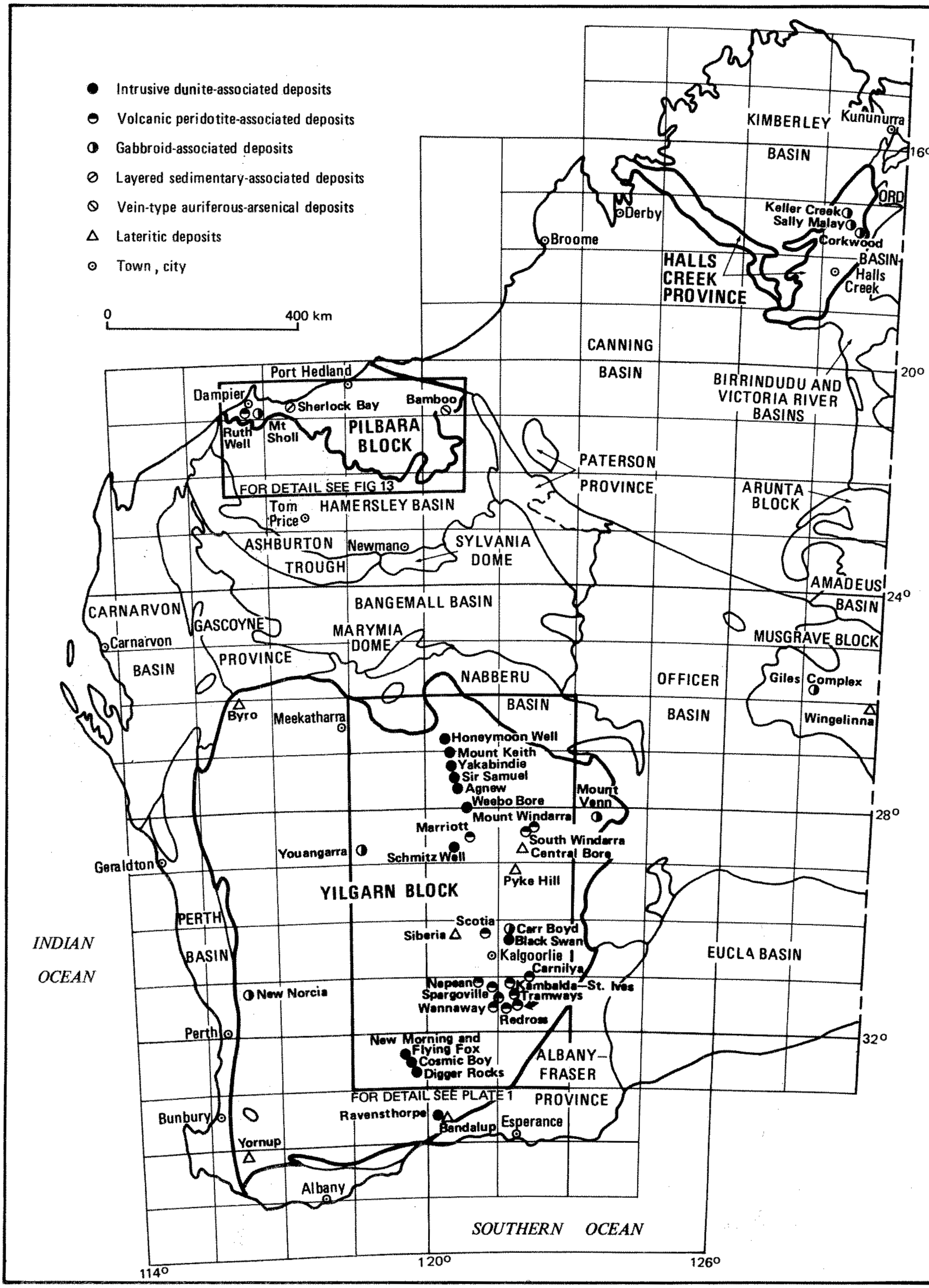

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Figure 3. General distribution of nickel deposits in Western Australia.

Australia) to be 56 Mt averaging 1.24 per cent nickel and 0.09 per cent cobalt; this does not constitute an economic deposit in such a remote area.

In 1947, while prospecting for gold around old workings in the vicinity of the long-abandoned townsite of Kambalda (named in 1897), George Cowcill collected some green-stained ferruginous rock specimens from spoil dumps of the old Red Hill gold mine on the shores of lake Lefroy. Interest in uranium was high in 1954 and Cowcill re-examined his specimens which he though might contain uranium, as they resembled some green samples containing secondary uranium minerals that were on display in Coolgardie. Cowcill and a friend, John Morgan, submitted them for analysis to the Kalgoorlie School of Mines in late 1954. Uranium was not detected, but the presence of nickel was reported by W. H. Cleverly, who recommended exploration and the collection of more samples. Cowcill submitted another sample in early 1955 which Cleverly described as "an ironstone of sulphide derivation with a few greenish stains which gave a positive test for nickel". Nothing more was done until September 1964, when Morgan (now in partnership with Cowcill) submitted further samples from the same location to Roy Woodall, then assistant chief geologist with WMC at Kalgoorlie, but the earlier reports by Cleverly were not attached. Since 1962 WMC had been conducting a gold and base metals search by extending a detailed geological mapping programmes southwards from Kalgoorlie following the gold-bearing belt of mafic-ultramafic rocks. By 1964 mapping parties had almost reached Kambalda, thus arousing Morgan's interest. The samples assayed up to 1 per cent nickel, and were also recognized by Woodall as gossans that might be the surface expression of a sulphide deposit at depth.

The sample locality at the Red Hill gold workings was inspected and several small isolated outcrops of limonitic gossan were found over a strike length of 450m. the outcrops are about 30 cm wide with some disseminated limonite up to 60 cm into the overlying oxidized ultramafic rock. The existence of a gently dipping sulphide layer associated with the ultramafic rock was indicated by these outcrops, and mapping showed that the limonitic zone was at the base of the ultramafic at its contact with underlying metabasalt (Woodall and Travis, 1969). Further mapping revealed a domal structure delineated by the outcrop of the basal contact of the ultramafic. Other nickeliferous gossan outcrops were found at or near this contact, which was traced for a strike length of some 21 km around the dome. Geophysical and geochemical surveys were also undertaken around the contact zone. In December 1965, the first of several diamond drill holes (KD1), designed to investigate the nature of the sulphides below the gossanous outcrops, was sited near the original gossan discovery at Red Hill gold mine. On 28 January 1966, while Jack Lunnon was in charge of drilling this hole, a core of massive sulphides was lifted which returned an assay of 8.30 per cent nickel and 0.51 per cent copper over a length of 2.75m. Althought barren intersections were encountered in several drillholes that followed, further drilling eventually indicated than an important massive nickel sulphide deposit (Lunnon shoot) had been found, and WMC announced the discovery on 4 April 1966.

In July 1966 sinking of the Silver Lake shaft began, close to the discovery site of Lunnon shoot by drillhole KD1. The first ore production resulted in March 1967. Ore reserves at mid-year were quoted as 2.489 Mt averaging 4.18 per cent nickel (Lunnon shoot only). A small concentrating plant was commissioned in the following May, with the initial consignment of nickel concentrate being shipped from Esperance on 2 August for refining in Canada by Sherritt Gordon. The new mine was officially opened on 15 September 1967. Development of a second deposit, 5 km northwest of Lunnon shoot, began in December 1967 with the sinking of the Durkin shafts. Nickel ore production in the second half of 1967 was 67 472 t averaging 4.57 per cent nickel which was treated to produce 16 005 t of concentrates averaging 13.00 per cent nickel. Only a small amount of this concentrate was sold in 1967 (Table 1). Mine production in 1968 was similar, but Lunnon shoot remained the only supplier.

WMC's success at Kambalda, coupled with a buoyant demand for nickel, initiated a speculative boom in nickel exploration. Large areas were claimed as tenements for nickel and other base metal exploration by individual prospectors, Australian companies (many floated solely for the purpose), and international mining companies with worldwide interests. Ground with evidence of mafic and ultramafic rocks was the most keenly sought, but at the height of the boom in 1969-1970 much ground was pegged that had little or no prospectivity. Important discoveries were made in the Broad Arrow (north of Kalgoorlie), Coolgardie and Widgiemooltha areas in 1967-1968 (plate 1).

In May 1968 the Jones family syndicate entered into an option agreement with the Great Boulder (51 per cent) and N. Kalgurli (49 per cent) partnership covering the nickel discovery by J Jones, east of Scotia Siding, some 64 km north-northwest of Kalgoorlie. Shallow drill holes put into the mineralized zone by the Jones syndicate in February had averaged 2.54 per cent nickel and 0.34 per cent copper. Plans to mine the Scotia deposit were announced in August 1968 following a diamond drilling programme from which an indicated sulphide ore reserve estimate of 1.13 Mt averaging 3.07 per cent nickel and 0.25 per cent copper was made. Shaft sinking began in September 1968, and, just over a year later, in October 1969, production was achieved at a rate of 10 000 t of ore per four-week period. Great Boulder converted its disused gold treatment plant at Fimiston to a nickel treatment mill and in February 1970 the first load of ore was carted from Scotia.

By May 1969 ore haulage had begun from the Durkin shafts at Kambalda, making Durkin the State's second producing mine. In the same month that Scotia began production, a new type of mine started producing ore from a decline situated 1 km west of the Durkin shafts. The commencement of this decline, known as the Otter-Juan decline, took place in June 1969 and it was planned to develop a series of near-surface, gently dipping ore shoots (Palmer, 1973) beginning with Otter shoot. The adoption of a decline system also allowed quick production and a better short-term cash flow compared with a vertical shaft mine, both important factors at that stage in Kambalda's growth. The State's nickel production in 1969 was some 50 per cent greater than in 1968 (Table 1), Lunnon and Durkin shoots being the only large producers that year.

TABLE 1. ANNUAL PRODUCTION OF NICKEL ORE AND CONCENTRATES, COPPER AND COBALT BY-PRODUCTS, WESTERN AUSTRALIA 1967-1980

Year	Nickel ore & concentrates (t)	Average nickel content (%)	Contained nickel (t)	Contained copper (t)	Contained cobalt (t)
1967	2 288.98	12.94	296.19	—	—
1968	45 997.40	11.92	5 482.89	741.93	92.83
1969	68 729.68	11.46	7 876.42	933.35	87.39
1970	310 446.23	10.34	32 094.42	2 125.30	338.06
1971	386 255.91	9.46	36 532.85	954.11	205.67
1972	309 180.00	10.23	31 643.83	724.61	193.53
1973	353 172.49	11.40	40 246.48	372.00	131.43
1974	437 048.61	10.95	47 854.65	267.00	135.00
1975	481 846.00	10.84	52 230.63	678.00	57.28
1976	530 826.00	10.93	58 036.87	1 419.97	194.80
1977	527 129.00	10.73	56 578.48	1 830.90	200.66
1978	468 941.00	11.48	53 810.09	1 501.42	172.29
1979	479 119.00	11.25	53 910.34	1 740.81	215.86
1980	483 099.00	10.69	51 661.83	3 132.40	982.65
Total to end 1980	4 884 079.30	10.82	528 255.97	16 421.80	3 007.45

Notes:

1. Figures relate to production which is reported as sold in that year and may not reflect actual annual mine production.
2. Tonnages of copper and cobalt are as measured in refinery products only.

Development of a fifth nickel mine also began in 1969, this time some 56 km west of Kambalda at Nepean, near Coolgardie. Tenements were first taken up by Metals Ex (50 per cent, managers) and Freeport (50 per cent) in late 1966, but the first diamond drill hole was not begun until December 1967, following geological, magnetic and induced polarization surveys. No mineralization was encountered in the first, or initially in the second drillhole. In March 1968, the third drillhole (ND3) intersected 5.63 per cent nickel over a core length of 1.07m and at a drilled depth of 191 m. The discovery was not related to a gossan find. The initial target was based on geophysical anomalies, later found to be related to sulphidic metasedimentary rocks and ultramafic rocks neither of which were directly associated with the mineralization (Sheppy and Rowe, 1975). The mineralization and its host ultramafic were discovered as a result of a decision to extend the drillhole beyond the initial target. The second drillhole (ND2) was deepened in May, and 1.43 m of sulphide mineralization assaying 5.27 per cent nickel was intersected at a drilled depth of 206 m.

By 30 September 1968 drilling had outlined mineralization over a strike length of 600 m, and a decision to establish a mine was made in December. Initial ore reserves were estimated at 400 000 to 500 000 t averaging a little more than 4 per cent nickel. Shaft sinking began in February 1969, and following an agreement with WMC the first ore was carted, in January 1970, for treatment at Kambalda. Production of about 6 000 t of ore per month was attained by July.

Large increases in production (achieved by a high rate of development) at the three major mines operating at Kambalda (Otter-Juan, Durkin and Silver Lake), and the attainment of full production at the smaller mines of Scotia and Nepean enabled the State's contained nickel output to surge ahead to 32 000 t in 1970. Diamond drilling at Kambalda indicated at least two new ore shoots on the west side of the dome, and a new shoot (Hunt) at the south end, parallel to Lunnon shoot.

Anaconda (60 per cent) in partnership with CRA (26.6 per cent) and NBHC (13.3 per cent) announced the discovery of important mineralization (Widgie 3 deposit; 907 184 t averaging 1.2 per cent nickel) near Widgiemooltha in May 1967. In late 1970 shaft sinking began at two larger deposits to the south at Redross (907 184 t averaging 3.5 per cent nickel) and Wannaway (3.628 Mt averaging 1.2 per cent nickel), and preliminary surface installations for mining were completed in 1971, but an inability to find suitable marketing contracts led to a suspension of production plans. Redross mine finally achieved full production in late 1974. Similarly the Carr Boyd deposit, discovered in 1968 and fully developed for production by mid-1972 was to remain idle until July 1973. Two further discoveries made in 1967 in the Widgiemooltha area were by the INAL-BHP joint venture at Mount Edwards, and by Selcast at Spargoville. Production was finally achieved at Spargoville in March 1975, nearly five years after shaft sinking began. A combined exploration-production shaft was sunk at Mount Edwards in 1969-1971, but following a small amount of exploratory driving and underground drilling the installations have remained on a care and maintenance basis since March 1972.

The year 1971 was largely one of consolidation in terms of ore production. Output rate from Kambalda and Nepean was similar to that of the previous year. Development of two new decline mines began at Kambalda. This was to enable exploitation of the McMahon-Gellatly-Ken and Fisher complexes of ore shoots on the western side of the Kambalda dome. Further underground development at Scotia and a full year's production made possible a near doubling of nickel production from this mine compared with 1970. Glory hole development of the near surface portion of No 1 shoot at Carr Boyd yielded a small amount of ore which was put through the Fimiston mill in 1971-1972.

Important events were also reported from the North-eastern Goldfields in 1971. At Mount Windarra, near Laverton percussion drilling by Poseidon in September 1969 of a small gossan found by K Shirley, intersected nickel-copper sulphides in what proved to be the A shoot (Robinson and others, 1973). Subsequent drilling revealed four additional shoots and in December 1970 an exploratory winze was begun on A shoot. Work on a decline mining complex began in May 1971. The discovery by drilling in November 1970 of a similar, but blind, mineralization, 15 km south of Mount Windarra at the South Windarra locality had an important impact on development planning. On 28 October 1971 an agreement for the joint development of the two mineralized areas was signed between Poseidon and the Union Oil — Hanna — Homestake consortium. The agreement was nullified in 1972 and Poseidon took control of South Windarra also. When preliminary production began in late 1974, total mineable ore reserves for both areas were estimated at 8.7 Mt averaging 1.94 per cent nickel (1 per cent nickel cut-off).

Further north at Agnew (330 km north of Kalgoorlie) in May 1971 W. Selcast discovered a deposit in May 1971 which proved to be immense, being comparable in size to the aggregate of deposits at Kambalda-St Ives with a content of nickel metal approaching the one million tonnes mark.

The announcement of a significant discovery was made in June, following the completion of a series of shallow percussion drill holes (near the gossan) which intersected mineralization assaying 1 to 2 per cent nickel over true widths greater than 88 m. By July the mineralized zone was extended to 365 m in strike length and six diamond drillholes had intersected mineralized widths of 5.7 to 22.9 m assaying between 1.68 and 4.68 per cent nickel on average. In November, indicated ore reserves of 9 Mt containing 2 per cent or more nickel were announced. In July 1972 this figure was increased to 23 M averaging 2 per cent nickel, and again to 33 Mt averaging 2.2 per cent in December 1972, with the addition of reserves in the No 2 shoot which occurs beneath the originally discovered No 1 shoot. When production of development ore began in early 1978 the reserves were stated as 45 Mt averaging 2.05 per cent nickel.

State production of contained nickel was 13 per cent lower in 1972 compared with the previous year, although production at Scotia and Nepean did rise (Tables 1 and 2). At Kambalda industrial disputes during the year, and a reduction in the head grade of ore milled were the main factors responsible for the decline. Revaluation of the Australian dollar, an oversupply of nickel on the World market, and a seamen's strike which delayed concentrate deliveries to Japan, all contributed to a considerable fall in the profitability of WMC's nickel operations. Actual ore production was less at Nepean, but the introduction of rill stoping in the lower levels allowed more selective mining and reduced dilution from unsupported stope walls, thus the average head grade increased from 2.23 to 2.70 per cent nickel. The McMahon and Fisher decline mines at Kambalda began contributing to production in the latter half of 1972.

A recovery to the 1971 level of production took place at Kambalda in 1973, although the head grade of ore mined continued to fall. A start was made in June on a new decline on Hunt shoot at the southern end of the Kambalda dome, and at St Ives on the southern side of Lake Lefroy preparations for shaft sinking on Jan shoot commenced in September. Drilling on the east flank of the Kambalda dome outlined the newly discovered Gibb, Long and Victor shoots. The Anaconda consortium obtained a contract with Sherritt Gordon for the sale of nickel concentrates, and this allowed further underground development and site work to resume at the Redross mine in May 1973; the mine had been on care and maintenance since May 1972. By the end of 1973 N. Kalgurli's gold milling plant at Kalgoorlie had

TABLE 2. INDIVIDUAL REALIZED MINE PRODUCTION OF NICKEL IN CONCENTRATES (TONNES), 1967-1980

Mine / Year	Kambalda-St Ives group	Nepean e	Scotia	Carr Boyd	Redross	Spargoville	Mt Windarra S Windarra	Agnew
1967	296.19a							
1968	5 482.89a							
1969	7 876.42b							
1970	29 686.23b	1 243.12	1 165.06					
1971	32 551.89b	1 833.49	2 118.13f					
1972	26 896.26b	1 955.19	2 783.89f		28.49g			
1973	33 860.84c	2 466.42	3 522.59	389.48	7.15			
1974	41 357.76c	2 311.38	1 387.41	1 085.15	1 712.95			
1975	36 857.39d	2 474.71	1 625.46	479.28	2 889.81	1 195.46	7 903.98	
1976	33 783.99d	2 141.41	1 535.33	Nil	4 080.10	1 980.18	14 499.12	
1977	36 810.50d	2 350.74	489.97 Closed on September 8	192.22 Closed on September 2	3 225.88	2 864.93	10 640.64	
1978	40 242.01d	2 441.25	Nil	Nil	1 198.11 Closed on May 31	1 801.86	4 295.91 Mining ceased February 17 (S W), June 30 (M W)	Production began August 1
1979	42 718.40d	2 422.86	Nil	Nil	Nil	2 059.53	376.58	6 332.97
1980	35 996.82d	3 133.65	Nil	Nil	Nil	2 676.30		9 855.16
Total	404 417.59	24 774.22	14 627.84	2 146.13	13 142.49	12 578.26	37 716.23	16 188.13
Per cent of grand total	77.0	4.7	2.8	0.4	2.5	2.4	7.1	3.1

Notes:

a Quantity of nickel in concentrates sold and shipped from WA.

b Quantity of nickel in concentrates (i) sold and shipped; (ii) sent to Kwinana refinery.

c Quantity of nickel in concentrates (i) sold and shipped; (ii) sent to Kwinana refinery; (iii) sent to Kalgoorlie smelter.

d Quantity of nickel in concentrates treated at refinery and smelter.

e Quantity of nickel in ore treated at Kambalda.

f Figures include 104.62 t nickel in development ore from Carr Boyd, 1971-1972.

g Figure includes nickel in development ore from Wannaway.

been converted to enable the ore from Redross to be concentrated. Earlier in 1971 an option agreement was signed for N. Kalguri to treat ore from Selcast's deposit at Location 3 (or 5D), Spargoville, where shaft sinking began in May 1971 based on a mineable reserve of 650 000 t averaging 2.47 per cent nickel. Production from this deposit was originally planned for 1973, but severe groundwater inflows delayed shaft sinking so that production did not eventuate until early 1975. Initially it was planned to mine out by decline the nearby Location 2 (or 5B) deposit (119 000 t mineable reserve averaging 2.32 per cent nickel) just before the Location 3 deposit began producing in 1973, but a high arsenic content (with attendant metalurgical and sales problems) obliged Selcast to stop operations at the decline mine in September 1972.

Underground development at Carr Boyd mine was suspended in mid-1972, because of the lack of a sales contract for the high-copper concentrates. A three-year sales contract was signed with WMC in June 1973 and limited production then began, based upon reserves of 1.086 Mt averaging 1.60 per cent nickel and 0.56 per cent copper. Production was below the expected figure mainly because of a shortage of skilled miners. Production of contained nickel reached a peak at Scotia in 1973, and a substantial increase was also recorded at Nepean (Fig. 2; Table 2).

Record production (of nickel in concentrates) was achieved at Kambalda in 1974 despite a slight fall in the head grade of ore mined. Otter-Juan, Silver Lake and Durkin mines continued as the major producers. A more efficient method of ore treatment was introduced at the mill in mid-year. Shaft sinking began early in the year at Jan and Edwin shoots, south of Lake Lefroy. At Nepean production fell slightly because of problems experienced in employing sufficient numbers of skilled miners, and owing to difficulties in moving dry fill into narrow stopes. Similar labour problems were felt at Redross in its first year of full production, during which, output of nickel in concentrates was only a little over one third of the originally planned figure of 4 500 t per annum. Excessive wall rock dilution occurred also, and the mine barely achieved a financial break-even point for the year.

Carr Boyd mine also performed well below expectations in 1974 during its first full year of production, and substantial working losses were incurred by the Great Boulder — N. Kalgurli partnership. These difficulties were compounded by a floor pillar collapse just below the 201 m level at Scotia mine on 16 May 1974, which eventually precipitated a hanging wall collapse on July 9th and consequently restricted mining to operations below the 253 m level. As a result, production for the year was only 40 per cent of the 1973 production. The situation aggravated the strained relationships between the partners, which culminated in Great Boulder claiming a right to 100 per cent control of all joint venture operations as from 11 October 1974. After a protracted dispute in the courts, Great Boulder eventually did gain full control in March 1975.

Development work towards achieving production at an annual rate of 14 000 t nickel in concentrates (equivalent to about 1.2 Mt of ore) from the Windarra deposits accelerated in 1973-1974, following the acquisition by WMC of a 50 per cent interest in the project in mid-1973. Production commenced on 11 September 1974 following completion of commissioning of the nickel concentrator. The concentrator treated 186 406 t of ore in 1974 (not reported until 1975), being 126 759 t from Mount Windarra decline mine and 59 647 t from South Windarra open cut mine, from which 17 000 t of concentrates were produced. Windarra became the second largest producer in the State (Fig. 2). Following the removal of nearly 6 million cubic metres of water-bearing alluvial overburden and oxidized rock, mining at South Windarra proceeded by conventional quarrying methods using airtrac drills and front-end loaders on 10 m high benches. On 16 July 1975, Poseidon (through its subsidiary Windarra Nickel Mines Pty Ltd) relinquished control as manager to WMC.

Windarra achieved 86 per cent of its target rate of annual production in 1975, despite bad ground conditions encountered in the main production stopes at Mount Windarra. Production was increased at South Windarra in an effort to compensate. Actual production at Windarra was about 12 000 t of nickel, some of which was reported in 1976. Concentrates were hauled by road and rail to the nickel smelter at Kalgoorlie or exported via Esperance.

At Kambalda, output of nickel in concentrates in 1976 was 90 per cent of the peak figure of 41 358 t in 1974. The first ore production from Jan mine, south of Lake Lefroy, came in December 1975, and shaft sinking at Long shoot on the east side of the Kambalda dome began in July 1975. Spargoville mine began ore production at the end of March, following development work on four underground levels undertaken the previous year. Some 68 087 t of ore averaging 2.71 per cent nickel was mined in the first full year, which was less than half the planned output rate of 160 000 t a year. The operating companies at Spargoville, Nepean, Redross and Carr Boyd all blamed shortfalls in production on a shortage of experienced miners and technical difficulties involved in mining and backfilling small, steeply inclined orebodies. The introduction of hydraulic sand-filling of stopes alleviated the problems in some cases. Mining at Carr Boyd was suspended on 17 June 1975 and the plant was put on care and maintenance. Remaining ore reserves were quoted as 552 000 t averaging 1.51 per cent nickel and 0.49 per cent copper. Following discussions initiated in May 1975, Great Boulder became a wholly owned subsidiary of WMC on 18 February 1976. Carr Boyd and Scotia mines therefore came under the full control of WMC.

The upward trend in State nickel production (Fig. 2) continued in 1976. Eight producing shaft or decline mines were in operation at Kambalda, namely Otter-Juan, Silver Lake, Durkin, Hunt, Fisher, McMahon, Jan and Edwin. An active exploration and development diamond drilling programme had enabled WMC to maintain ore reserves at Kambalda at between 700 000 and 800 000 t of contained nickel during the 1970s (Fig. 2, Table 3). Output of concentrates and nickel was less in 1976 at Kambalda compared with 1975 but this was offset by the 14 500 t nickel in concentrates reported from Windarra. Actual production was very similar to that of 1975, being about 1 Mt of ore, and this was achieved despite some loss of production at Mount Windarra because of a partial collapse of a floor pillar in the D shoot workings. However, in a

TABLE 3. PUBLISHED DEMONSTRATED ORE RESERVES IN TONNES OF CONTAINED NICKEL, 1966-1980

Mine Year	Kambalda- St Ives Group	Nepean	Scotia	Carr Boyd	Redross	Spargoville	Mount Windarra	South Windarra	Agnew
1966	80 163 (1.930 Mt, 4.15%)								
1967	104 049 (2.489 Mt, 4.18%)								
1968	359 290 (9.455 Mt, 3.8%)	ca. 18 000 (0.4-0.5 Mt, 4%)	34 691 (1.13 Mt, 3.07%)						
1969	586 450 (15.850 Mt, 3.7%)	ca. 18 000 (0.4-0.5 Mt, 4%)	34 691 (1.13 Mt, 3.07%)	22 453 (1.361 Mt, 1.65%)	31 751 (0.907 Mt, 3.5%)		96 000 (4 Mt, 2.4%)		
1970	593 062 (17.443 Mt, 3.4%)		34 691 (1.13 Mt, 3.07%)	28 651 (2.032 Mt, 1.41%)	31 751 (0.907 Mt, 3.5%)	16 021 (0.649 Mt, 2.47%)			
1971	710 430 (20.895 Mt, 3.4%)		31 311 (1.06 Mt, 2.94%)	25 786 (1.829 Mt, 1.41%)	31 751 (0.907 Mt, 3.5%)	16 021 (0.649 Mt, 2.47%)			180 000 (9 Mt, 2%)
1972	746 830 (22.7 Mt, 3.29%)	15 748 (0.508 Mt, 3.10%)	26 001 (1.238 Mt, 2.10%)		34 431 (0.984 Mt, 3.5%)	16 021 (0.649 Mt, 2.47%)		169 094 (9.042 Mt, 1.87%)	726 000 (33 Mt, 2.2%)
1973	779 220 (24.05 Mt, 3,24%)	21 560 (0.490 Mt, 4.4%)	18 007 (1.029 Mt, 1.75%)	17 376 (1.086 Mt, 1.60%)	29 414 (0.840 Mt, 3.5%)	16 021 (0.649 Mt, 2.47%)	108 870* (5.7 Mt, 1.91%)	62 080* (3.2 Mt, 1.94%)	880 000 (40 Mt, 2.2%)
1974	790 510 (24.55 Mt, 3.22%)		11 653 (0.555 Mt, 2.10%)	12 776 (0.794 Mt, 1.61%)	26 894 0.768 Mt, 3.5%)	15 728 (0.493 Mt, 3.19%)	108 080* (5.6 Mt, 1.93%)	62 720* (3.2 Mt, 1.96%)	960 616 (47.321 Mt, 2.03%)
1975	792 933 (24.549 Mt, 3.23%)	12 876* (0.348 Mt, 3.7%)					97 500* (5.0 Mt, 1.95%)	55 180* (3.1 Mt, 1.78%)	
1976	778 688 (24.334 Mt, 3.20%)		3 600 (0.219 Mt, 1.64%)	8 335 (0.552 Mt, 1.51%)			92 222* (5.3 Mt, 1.74%)	43 491* (3.815 Mt, 1.14%)	
1977	709 233 (22.233 Mt, 3.19%)	17 480* (0.437 Mt, 4%)	2 505 (0.164 Mt, 1.53%)	8 494 (0.559 Mt, 1.42%)		13 368 (0.512 Mt, 2.61%)	92 568* (5.51 Mt, 1.68%)	31 680* (2.88 Mt, 1.10%)	
1978	687 495 (21.219 Mt, 3.24%)	12 010* (0.301 Mt, 3.99%)					89 080* (5.638 Mt, 1.38%)	26 378 (2.561 Mt, 1.03%)	922 500 (45 Mt, 2.05%)
1979	688 800 (21.000 Mt, 3.28%)	9 360* (0.240 Mt, 3.9%)					91 450* (5.90 Mt, 1.55%)	25 750* (2.5 Mt, 1.03%)	
1980	708 480 (21.600 Mt, 3.28%)						102 510* (6.70 Mt, 1.53%)	25 750 (2.5 Mt, 1.03%)	

Notes:

1. * = mining reserve, allows for loss and dilution.
2. Cut-off figure is 1.0 per cent nickel, excepting Nepean which is 1.5 per cent.
3. Nepean reserves include inferred reserves.

world-wide climate of rapidly increasing production costs (estimated by WMC to be increasing by 25 per cent a year at Kambalda) and fierce price competition in the nickel market, Windarra Nickel Mines Pty Ltd (Poseidon) incurred large financial losses in the year 1975-1976 and went into receivership in October 1976. Poseidon's half share in the Windarra operations was purchased by Shell in August 1977.

Redross and Spargoville mines both increased output in 1976, but the increases were only to 78 per cent and 57 per cent respectively of the planned capacities. Scotia and Nepean mines produced slightly less nickel in concentrates than in 1975.

In June 1974, Mount Isa Mines Ltd had acquired a 40 per cent interest in the Agnew nickel project, as a joint venturer with W. Selcast. The joint venturers formed the Agnew Mining Company Pty Ltd (AMC) as the management company for the project. A decision of the viability of the project was deferred until February 1976, when plans were made to produce 10 000 t a year of nickel in concentrates from a decline into the massive ore of 1A shoot. Concurrent with the driving of the decline it was planned to sink an exploration shaft (designed for ultimate use as a production shaft) to allow examination of the 2 shoot disseminated orebody at depth. By the end of the year 29 m of shaft sinking (intended final depth 910 m), and 220 m of decline development had been accomplished, despite bad ground conditions which slowed work on the decline and necessitated change in its route. Full details of development and production plans were released in October when agreement had been reached with WMC for the toll smelting of up to 100 000 t a year of concentrates. This was to begin in 1979 following the construction of a new flash furnace at the Kalgoorlie smelter, at a cost of A$30 million of which $20 million would be provided by

AMC. In July 1977 a contract was signed with Amax Nickel Inc for the sale of up to 15 000 t a year of nickel (in nickel matte) over a period of 10 years from the beginning of commercial production. The initial shipment of matte was dispatched in December 1978.

In October 1976 a small-scale open-pit mine was begun at Siberia (80 km north of Kalgoorlie) to provide silica-rich nickeliferous laterite to replace silica sand as flux in the Kalgoorlie smelter. Nickel in the flux is recovered in the smelting process, so this material can be regarded as nickel ore. Nearby, in the period November 1978 to March 1979, some 62 500 t of cobalt-rich laterite averaging 0.34 per cent cobalt and 1.2 per cent nickel were extracted by WMC from a small open pit. This ore was used as direct feed for the smelter. Other such small deposits in the area have been similarly exploited.

Despite an upturn in production at Kambalda in 1977, State production declined to 97 per cent of the 1976 figure. Small-scale production began late in the year from very high-grade nickel ore in Gibb shoot on the eastern flank of Kambalda dome. The ore is extracted via a drive from Durkin mine, though surface access is provided by a raise-bored winze close to Long shaft. Preparations for sinking a shaft on Victor shoot, again on the eastern flank (south of Gibb shoot), were completed but further work was suspended because of a decision to curtail production in general. On 25 August 1977 WMC announced that it would reduce nickel production by about 10 per cent with effect from 2 September 1977 by suspending production at Scotia, Carr Boyd and Fisher (Kambalda) mines, and in some lower grade areas at other Kambalda mines. For Scotia and Carr Boyd this meant final closure. These events had little effect on State production in 1977. Production of contained nickel at Windarra decreased by a third during the year for two reasons. Firstly, with depletion of ore reserves in the pit established in the western portion of the South Windarra deposit, it was decided to remove waste overburden from the eastern portion of the deposit in preparation for a new pit. As a result ore output from the pit fell from 664 788 t in 1976 to 562 446 t in 1977. Secondly, in late 1977 mining at Mount Windarra was severely curtailed by the failure of a mass blast which was designed to produce some 230 000 t of broken ore in an open stope.

Redross mine produced throughout the year but output fell back to near the 1975 figure. Development of the mine had not kept pace with recent production which, added to the difficult marketing and mining cost situation, resulted in an announcement by the Anaconda consortium on 17 February 1978 that the mine would close on 31 May 1978. In contrast at Spargoville, improved and less labour-intensive mining methods resulted in a 50 per cent increase in nickel output, and the first year in which an operating profit was made by Selcast.

State production declined again in 1978, although an improvement in head grade, and the time lag involved in lower production rates becoming effective, resulted in little change in output from Kambalda. Further production cuts were decided on by WMC at the end of 1977 in the face of abnormally large stockholdings of unsold nickel and world nickel prices which had fallen below production cost, particularly in the case of low-grade deposits. With its high operating costs and low grade of ore Windarra was the obvious candidate for suspension, and on February 1978 WMC, as manager of the joint venture with Shell, announced that mining at South Windarra would cease that month, and that underground nickel production at Mount Windarra would stop on 30 June. However it was decided that at Mount Windarra exploration and underground development would continue in preparation for a resumption in production when world markets improve. Total output to date of nickel in concentrates at Windarra is about equivalent to one year's output from Kambalda-St Ives (Table 2).

The next casualty was the Redross mine which, as mentioned before, closed at the end of May 1978. Total production of nickel in concentrates amounted to 13 142 t, a little less than the total that was won from Scotia mine over a longer period (Table 2). This closure also affected N. Kalgurli which had been treating Redross ore in its Croesus plant, along with Selcast's ore from Spargoville which was concentrated in a separate circuit. Selcast was unable to support the Croesus plant alone, and on 31 May this company announced that hence-forward its nickel ore would be treated by WMC at Kambalda. Mining at Spargoville ceased in January 1980.

Financial difficulties were also evident at Nepean mine in 1978. A small operating surplus had been achieved here by Metals Ex over the years, but latterly this had been at the expense of development drilling to maintain ore reserves. The State Government offered a loan of $1 million to assist in this respect in August 1978. Production began at Agnew on 5 May 1978.

TREATMENT METHODS

Treatment of nickel ore in Western Australia began on 8 June 1967 when ore from the Silver Lake shaft at Kambalda was first fed into the concentrator, which had been commissioned on 29 May. Initial capacity was for beneficiating 130 000 t of ore a year, but this was quickly increased to 340 000 t by February 1969 and subsequent expansions have now increased the capacity to 1 625 000 t of ore a year. With the exception of an underground crushing station and service shaft commissioned at Otter-Juan in May 1976, all ore crushing and concentration at Kambalda takes place at a central milling complex.

Beneficiation at Kambalda consists of three-stage crushing followed by conventional and autogenous grinding, size classifying using screens and cyclones, flotation in cells, magnetic separation on drums, and finally thickening and spray drying to produce a dry nickel concentrate containing on average 12 per cent nickel and 1 per cent copper. The processes are summarized in Figure 4. Separate circuits are installed to deal with Kambalda ore, and ore from Nepean, Spargoville and trial parcels (e.g. Agnew). Although the plant is largely conventional, the introduction of autogenous grinding (rock impacting against rock instead of steel balls or rods), Maxwell-type flotation cells and spray driers was new to Australia. The commissioning of the first autogenous grinding section in late 1969 considerably reduced costs and increased output of the concentrator (Head, 1975). The magnetic separates

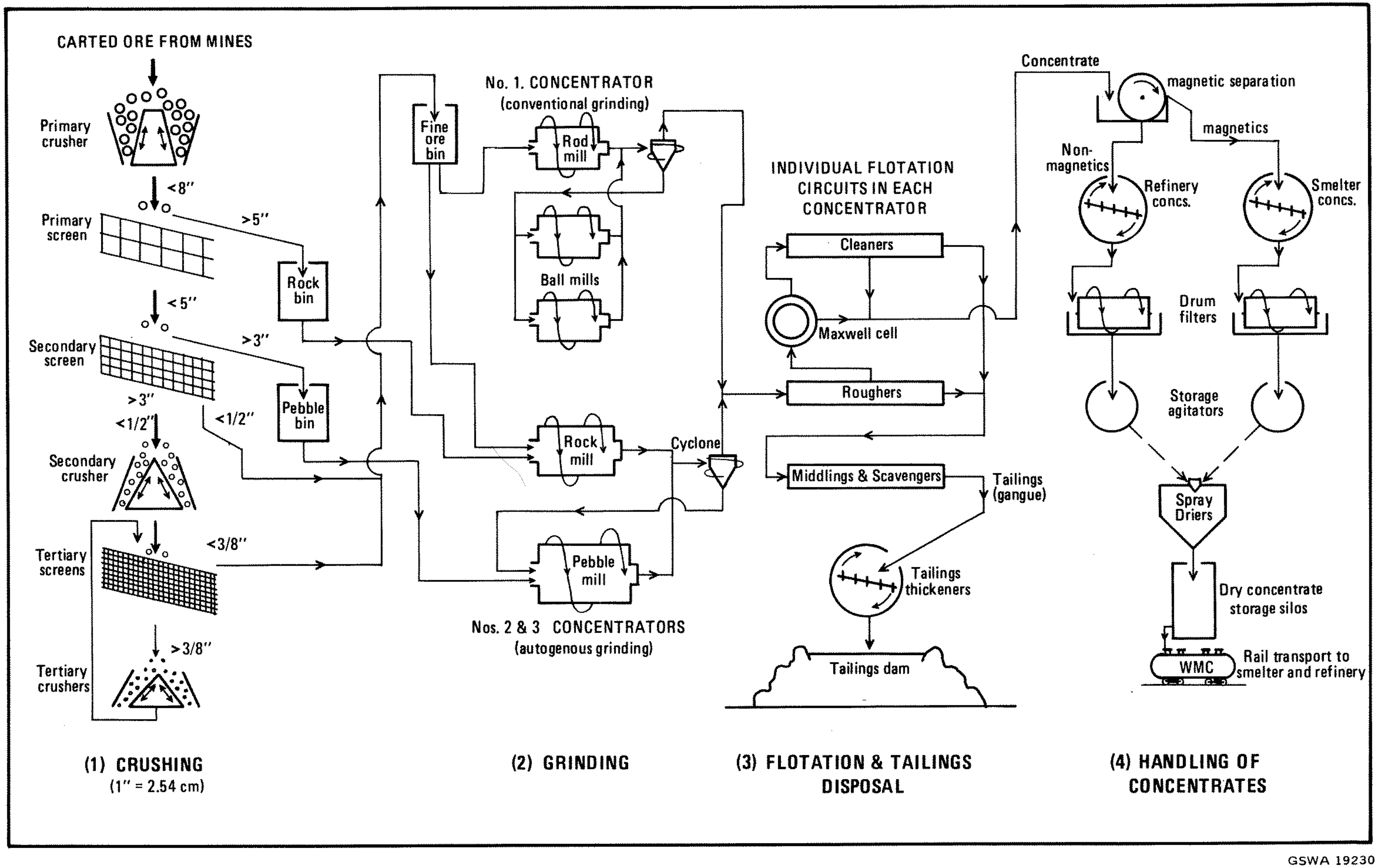

Figure 4. Diagrammatic representation of the ore concentrating plant at Kambalda (from O'Meara, 1979).

(pyrrhotite and magnetite) were stockpiled until the Kalgoorlie smelter came into operation in 1973. These seaprates contain about 1 per cent nickel and the pyrrhotite also acts as a fuel component because of its exothermic reaction with oxygen in air. Efforts are also being made to include as much pyrite as possible in the concentrates destined for the smelter, as most of the cobalt is contained in the pyrite and this cobalt is not recovered in the refining process. Pyrite also acts as a fuel during smelting.

The Kambalda mill is designed to deal with small amounts of supergene to transitional primary ore which contain the secondary nickeliferous sulphide mineral violarite. More oxidized ore containing sulphates or chlorides cannot be treated. Nickel sulphates may cause precipitates to form in the solution containing amyl xanthate used to collect (i.e. float off) sulphide minerals in the flotation cells. Chlorides, whilst not deleterious in the concentrating process, can cause corrosion and failure of the stainless steel vessels used in the refinery at Kwinana. All concentrates to be delivered to Kwinana are washed before being thickened and spray dried. A low magnesia content is an important factor in concentrates to be smelted or refined (Blanks, 1973), and organic seed oils are used in the flotation process to depress magnesium silicate minerals. Penalties are incurred for any more than trace amounts of arsenic present in concentrates. Fortunately arsenic is absent from many of the nickel ores at Kambalda, and only present in very small amount in the others. The arsenic content of Kambalda concentrates is in the range 50 ppm to 100 ppm, and the upper limit for feed to the refinery is 500 ppm (Blanks, 1973).

The concentrator at Windarra was commissioned on 11 September 1974, and was designed with a capacity range of 700 000 t to 1 000 000 t per annum. The maximum rate was quickly achieved and although initially the ores from Mount Windarra and South Windarra were treated in separate circuits, a combined throughput was introduced in late 1975. Nickel recovery improved from 65 to 80 per cent during the operating period. Concentrates averaged about 10.5 per cent nickel and 1 per cent copper. The basic concentrating process is similar to Kambalda, with the concentrates being finally flash dried before transport to Kalgoorlie.

The concentrating process used in treating nickel sulphide ores are similar to those employed in beneficiating sulphide ores containing gold. Both Great Boulder and N. Kalgurli converted their gold treatment plants at Kalgoorlie to handle nickel ores. Treatment involved conventional grinding only and did not include the thermal drying of concentrates. The Fimiston plant of Great Boulder began treatment of Scotia ore on 5 March 1970 with a planned throughput of about 120 000 t of ore a year. A little over 10 000 t of concentrates were produced in 1970 with an average assay of 11.43 per cent nickel. A separate circuit was installed at Fimiston to deal with ore from Carr Boyd. By early 1973 marked improvements in both circuits had been made with a nickel recovery in excess of 85 per cent being achieved. Concentrate grades from Scotia ore in the period 1974 to 1978 were on average about 15.6 per cent nickel and 0.7 per cent copper, and for Carr Boyd ore about 9.7 per cent nickel and 3.7 per cent copper.

Conversion of half of N. Kalgurli's Croesus plant began in June 1973 and on December the first parcel of Redross ore was treated, with a planned capacity for 13 000 t of ore a month. After being allowed to run down during the last few years of unprofitable gold mining, the plant was in need of general renovation. Additional flotation cells were installed and modifications made to the thickening, filtering and pumping equipment. The concentrates were shipped from Esperance for treatment at the Sherritt Gordon refinery in Canada. In mid-1974 the second stage of conversion began so that a separate circuit to treat Spargoville ore could be established. This circuit was commissioned on 28 February 1975. Total capacity of the plant was 350 000 t of ore per year, but as described above this was never attained because of shortfalls in ore production. Both circuits ceased operations on 31 May 1978 when the Redross mine closed. Since then nickel ore from Spargoville mine has been concentrated at Kambalda. The plant has subsequently been reconverted to treat gold-bearing ores. Concentrates of Redross ore averaged 15.4 per cent nickel, whereas those produced from Spargoville ore averaged 16.4 per cent nickel.

At Agnew, preliminary commissioning of the concentrator, designed to handle up to 300 000 t of ore per annum from the 1A shoot, began in March 1978. The ore is crushed in three stages to minus 10 mm, then stored in a 3 000 t fine-ore bin located ahead of the grinding circuit. This circuit comprises one large ball mill operating in conjunction with hydrocyclone size classifiers. Flotation cells produce a high-grade (11.0 to 14.5 per cent nickel) and a low-grade (2 to 3 per cent nickel) sulphide concentrate, the latter being rich in pyrrhotite. The high-grade concentrate is thickened, filtered and flash dried (using exhaust gases from the power plant), and stored in a 1 000 t silo, and then transported to the Kalgoorlie smelter. The first load was hauled southwards in August 1978. Initially, production of high-grade concentrate is planned to be 85 000 t per year, and total production of nickel in concentrate is expected to be more than 10 000 t per year. Low-grade concentrate which accounts for about 15 per cent of nickel contained in the ore, is dewatered and stockpiled for possible future retreatment. This concentrate will not be produced after mining of the 1A shoot finishes. When ore production from the shaft begins in 1982 the concentrator will have been expanded to process about 2.5 Mt of ore a year, producing some 220 000 t a year of concentrate. A second ball mill and tailing thickener, plus additional flotation cells are to be added to achieve this output.

In January 1968, six months after the production of concentrates at Kambalda began, WMC announced plans to build a refinery at Kwinana capable of producing 15 000 t per year of nickel. Production began in May 1970. Capacity has since been increased to 30 000 t per year of nickel. The Sherritt Gordon hydrometallurgical refining process was adopted mainly because of a need for low capital costs, rapid establishment and ease of expansion (Blanks, 1973) which are not features of pyrometallurgical (smelting-electrolytic refining) processes for nickel production. The hydrometallurgical process in use at Kwinana is summarized diagrammatically in Figure 5. The major differences between Kwinana and Sherritt Gordon's Fort Saskatchewan plant are as follows (Blanks, 1973).

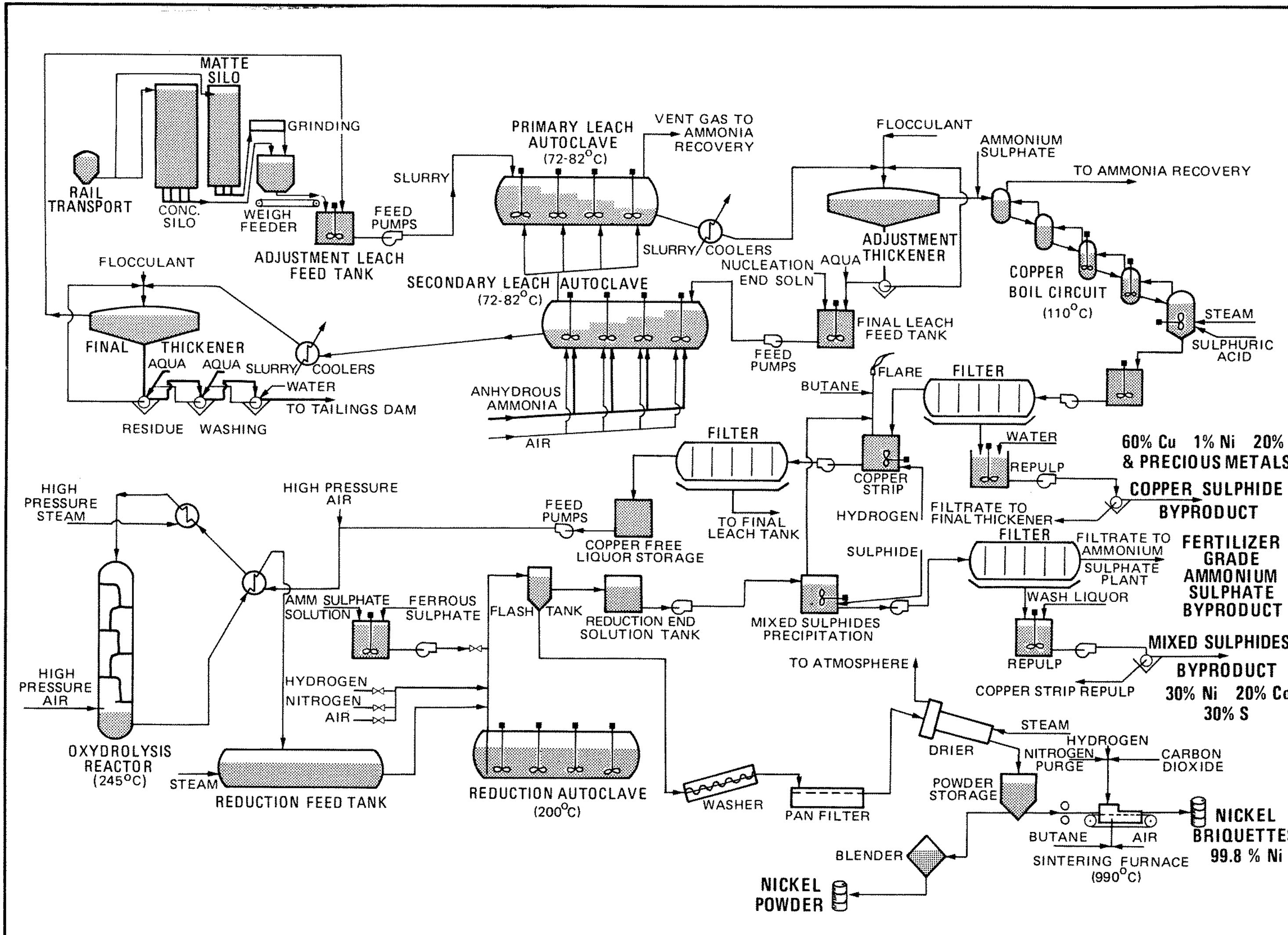

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Figure 5. Process flow chart for the Kwinana nickel refinery.

Kwinana employs pneumatic handling facilities for dealing with spray-dried nickel concentrates. There are fewer and larger leach autoclaves in use. The oxidation-hydrolysis step to remove remaining sulphur compounds is carried out in a tower at Kwinana instead of in autoclaves, and a centralized control is used to control the circuit from leaching through to oxidation-hydrolysis.

The Sherritt-Gordon process is a continuous ammoniacal pressure leach in which nickeliferous concentrate, ground matte or a mixture of concentrate and matte, is pumped as a 25 per cent solids slurry into stainless steel-clad autoclaves at 900 kPa with air and ammonia. In the year 1978/1979 refinery feed consisted of 83 000 t of concentrates and 21 000 t of matte. Soluble nickel-ammine complexes form with the iron remaining as hydrated iron oxide. The reactions are exothermic and cooling to 72°C to 82°C is necessary. The leaching is a two-stage operation with thickening and filtration of residues after each stage. The pregnant leach solution undergoes boiling ("copper boil circuit") at 110°C to remove copper which is precipitated as copper sulphide (60 per cent copper) co-product at a rate of about 3 000 t a year. Any remaining copper is precipitated by hydrogen sulphide. The copper-free liquor is then subjected to oxidation and hydrolysis at 245°C with air at 4.1 MPa, in the "oxydrolysis" reactor-tower. The residual unsaturated sulphur compounds are oxidized to sulphate, and ammonium sulphamate is hydrolyzed to ammonium sulphate which is later recovered in large quantity (about 100 000 t a year) as a fertilizer-grade by-product. Nickel is recovered in autoclaves by the hydrogen reduction at 3.15. MPa and 200°C of the now oxidized-hydrolyzed nickel diammine solution. The pure nickel precipitates as powder on seed nuclei, it is then washed, dried and either packaged for sale as such, or formed into briquettes and sintered at 950°C. The residual liquors from the reduction autoclaves are further treated with hydrogen sulphide to precipitate a mixed sulphide co-product (about 1 000 t a year) containing about 30 per cent nickel and 20 per cent cobalt. Ammonium sulphate is crystallized from the remaining metal-free liquor. Overall nickel recovery is better than 96 per cent.

The ammoniacal leach process is less versatile than smelting in treating different grades and types of concentrate and recovery of precious metals is incomplete (Blanks, 1973). Gold and platinum are little attacked in the leaching and therefore they remain in the leach residue and are not recovered. About half the silver and palladium present in concentrates is leached and precipitates along with the copper sulphides. The Kwinana refinery is currently operating well below its designed capacity: production in 1978/79 was some 21 400 t of nickel in powder and briquettes.

A decision to build a nickel smelter in the State was taken by WMC in late 1970. This was prompted by several factors. Since plans to build the refinery had been announced in early 1968, large additions had been made to the Kambalda ore reserves, the Scotia and Nepean mines had come into production and several important deposits had been found. It was evident that output of concentrates from Kambalda alone would soon exceed the refinery's capacity and the provisions of existing export contracts for concentrates. Production of a high nickel-content matte had economic advantages and such a product could also be used as a refinery feedstock.

Design for the smelter was based on the Harjavalta flash furnace in Finland, operated by Outokumpu. This company successfully carried out a full-scale trial on the smelting of Kambalda concentrates in 1972 (Blanks, 1973). Fuel economy was the main reason for choosing the Finnish design of smelter. Construction began at a site 13 km south of Kalgoorlie in early 1971, and the first concentrates were fed into the furnace on 5 December 1972. A process flow chart for the smelter is shown in Figure 6, and the three main metallurgical units involved are illustrated.

The principle exploited in a flash smelter is the simultaneous self roasting and smelting of a sulphide ore concentrate in an oxidizing medium, using the sulphur and iron content of the concentrate as the main fuel. The smelting temperature is attained in the reaction shaft (Fig. 6) by the instantaneous ("flash") combustion of iron and sulphur in preheated air (with or without oxygen enrichment). The nickel sulphides in the concentrate melt to form a matte, whereas the iron sulphides preferentially oxidize to iron oxide which in turn combines with the siliceous flux injected with the concentrate to form iron silicate slag. These liquids accumulate in the settler bath (Fig. 6). The nickel content of the matte is determined by regulating the ratio of air (oxygen) to sulphur in the feed. In the Kalgoorlie smelter the target grade at this stage is 50 per cent nickel plus about 3 per cent copper.

The initial design capacity of the smelter was 200 000 t a year of concentrate, using preheated air only as the oxidizing medium. In 1974 a 200 t per day oxygen plant was commissioned which increased the smelter's capacity by 509 per cent. A third converter, a second slag cleaning furnace and other ancillary equipment were added in 1975 to achieve a possible feed rate of 350 000 t per annum of concentrate. In 1975 280 000 t of concentrate were smelted for an output of 30 540 t of nickel in matte. Following the announcement in late 1976 that the Agnew deposit would proceed to production, it was decided to build a new larger flash furnace with an integrated slag-cleaning electric furnace (Fig. 6). This flash furnace was designed with a capacity to smelt up to 450 000 t of concentrates annually without the need for oxygen enrichment. It was commissioned on 15 November 1978. The old flash furnace is retained as a stand-by facility and for smelting of special feed (e.g. cobalt-rich material). The purpose of the electric furnace (Fig. 6) is to reheat the slag from the flash furnace and remove the contained nickel (1 to 2 per cent, largely as an oxide) by reduction with carbon. The nickel is then extracted as a low-grade matte containing about 40 per cent nickel. This matte and the higher grade matte tapped directly from the flash furnace are then fed into Pierce Smith type converters (Fig. 6). More silica flux is added and air is blown through the tuyeres to induce the same exothermic oxidation reactions taking place in the flash furnace. The resultant high grade matte (about 72 per cent nickel, 6 per cent copper) is poured off and granulated. Overall nickel recovery is better than 95 per cent. Matte also provides a good collecting medium for the precious metals in the feed.

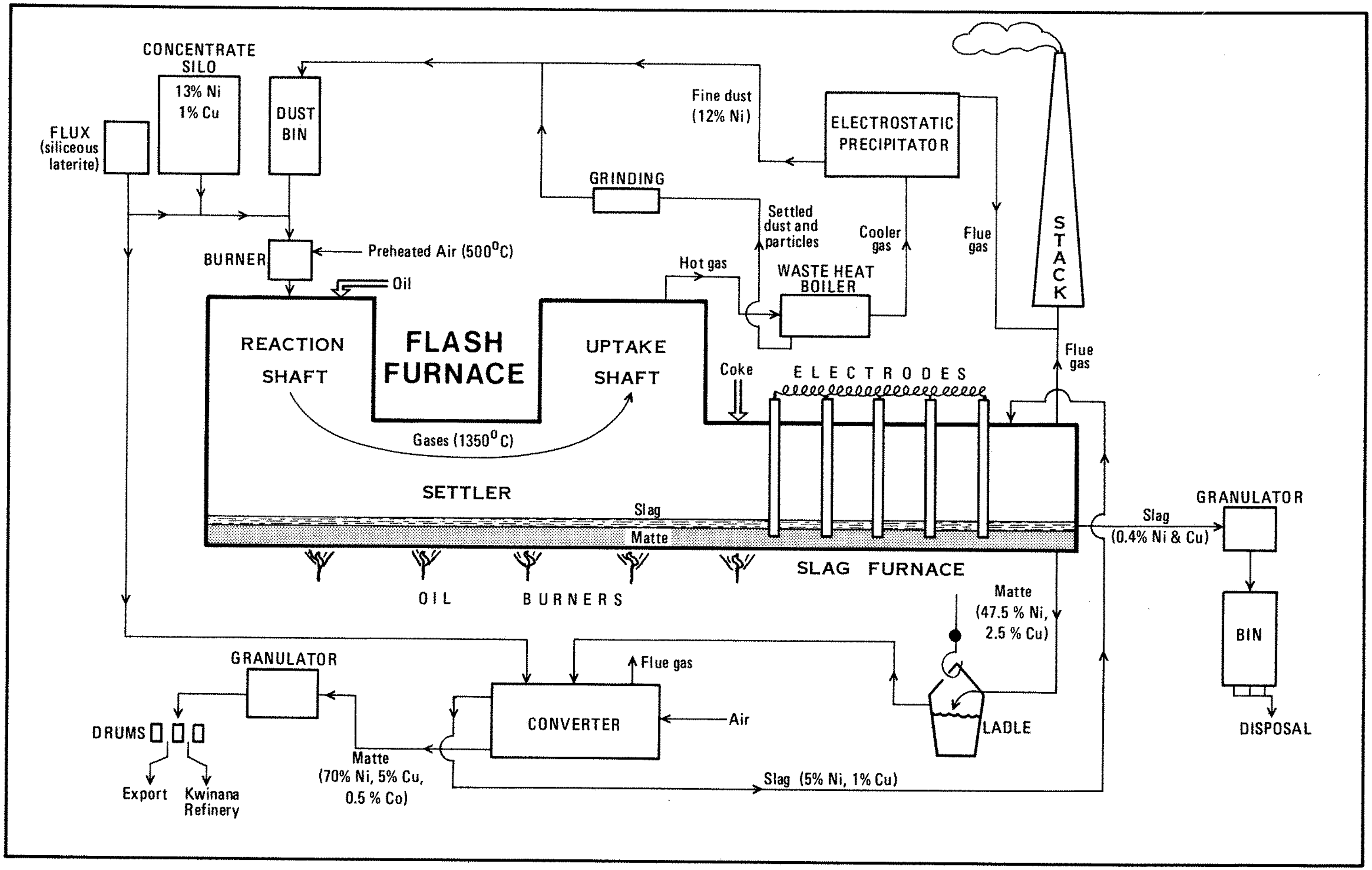

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Figure 6. Process flow chart for the Kalgoorlie nickel smelter.

It is important that the magnesia content of the concentrate feed be as low as practicable. This is because the melting point of the resulting olivine-rich silicate slag increases in direct proportion to magnesia content (Blanks, 1973), thus requiring more heat to keep the slag fluid and prevent accumulation of refractory deposits at the base of the furnace. The addition of small amounts of limestone to the silica flux helps to combat this effect (Segnit, 1976). In 1977 the use of sand as a source of silica flux was discontinued in favour of siliceous nickeliferous laterite mined at Siberia, which contains about 67 per cent silica and 1.3 per cent nickel.

The smelter is now increasing its annual consumption of concentrates from the 300 000 t mark of 1977-1978, as more concentrates arrive from Agnew. With the addition of oxygen enrichment the capacity could be nearly doubled from the present 450 000 t per annum.

It is worth noting that in all the treatment processes described, but particularly concentrating and refining, large amounts of fresh water are an essential ingredient. The Kambalda and Kwinana treatment plants are both supplied from Perth, though at Kambalda this source is supplemented by storm and reclaimed water. The Kwinana refinery draws about 3 500 kL per day from the metropolitan supply.

CHAPTER 2

Geochemistry and mineralogy of nickel

ABUNDANCE IN THE EARTH'S CRUST

The average abundance of nickel in the crust is only about 75 ppm, but ultramafic rocks, thought to represent samples of the Earth's mantle, average about 2 500 ppm, and meteorites considered equivalent in composition to the Earth's core contain some 8.6 per cent nickel (Table 4).

TABLE 4. AVERAGE ABUNDANCE ON A WORLD-WIDE BASIS OF NICKEL IN SOME COMMON ROCKS AND SEDIMENTS

Rock or sediment	ppm (or per cent where stated)	Source
Sideritic meteorite	8.59%	Mason, 1966
Chondritic meteorite	1.34%; 1.64%	Taylor, 1965; Mason, 1966
Earth's crust (largely continental)	75; 90; 58-75	Taylor, 1965; US Bureau Mines, 1975; Kästner and others, 1978
Crust (magmatic rocks)	58; 80	Vinogradov, 1962; Kästner and others, 1978
Ultramafic	2000; 1500	Vinogradov, 1962; Taylor, 1965; Goles 1967
Upper mantle peridotite	2652; 2435	Sato, 1977; Bickle and others, 1977.
Dunite	2187	Kästner and others, 1978
Peridotite	1167; 2000	Kästner and others, 1978; Turekian and Wedepohl, 1961
Pyroxenite	603	Kästner and others, 1978
Norite	300	Kästner and others, 1978
Gabbro	222	Kästner and others, 1978
Chilled border gabbros, layered intrusions	180	Wager and Brown, 1967
Mafic igneous	130; 160	Turekian and Wedepohl 1961; Vinogradov, 1962
Intermediate igneous	55	Vinogradov, 1962
Felsic igneous	8	Vinogradov, 1962
Basalt	150; 130	Taylor, 1965; Taylor, 1969
Tholeiitic basalt	185; 104	Prinz 1967; Kästner and others 1978
Island arc tholeiite	30	Jakeš and White, 1971
Oceanic tholeitte	97	Engel and others, 1965
Abyssal tholeiite	30-200	Jakeš and Gill, 1970
Alkali-olivine basalt	98; 220	Prinz, 1967; Kästner and others 1978
Andesite	18; 33	Taylor, 1969; Kästner and others, 1978
Syenite	5	Taylor, 1965
Nepheline syenite	7-40	Gerasimovsky, 1974
Diorite	76	Kästner and others, 1978
Granodiorite	20	Taylor, 1965
Granite	0.5; 6	Taylor, 1965; Kästner and others, 1978
Shale	68; 62	Turekian and Wedepohl, 1961; Kästner and others, 1978
Greywacke	50; 43	Taylor, 1965; Kästner and others, 1978
Sandstone	2	Pettijohn, 1963
Carbonate rocks	20; 12	Turekian and Wedepohl, 1961; Taylor, 1965
Deep sea clays	225; 176	Turekian and Wedepohl, 1961; Kästner and others, 1978
Deep sea carbonates	43	Kästner and others, 1978

Amongst crustal rocks, ultramafic igneous rocks rich in olivine or its altered equivalents have the highest contents of nickel, with most peridotites and dunites containing more than 2 000 ppm. Nickel contents decrease in the igneous series from ultramafic through mafic to felsic in both volcanic and plutonic rock types (Table 4). Subdivision of basalt into various types, distinguished largely on the basis of tectonic setting, reveals important differences in nickel content (Table 4). Tholeiitic basalt from the deep ocean floor may contain several times more nickel than basalt associated with volcanic island arcs. Deep-sea clays (Table 4) and manganese nodules (Table 5) are also enriched in nickel although the amount present is very variable. Other sedimentary rocks generally have low nickel abundances, although some black shales, and greywackes with a large component of mafic volcanic detritus, may contain 100 ppm nickel or more (Table 5).

The data in Tables 5, 6 and 7 on the nickel and magnesia contents of mafic-ultramafic igneous rocks are plotted on Figure 7. This reveals a close correlation between these two variables in both Archean and younger rocks.

TABLE 5. AVERAGE ABUNDANCE ON A REGIONAL BASIS OF NICKEL AND MAGNESIA IN SOME ROCKS AND SEDIMENTS

Rock or sediment	Nickel (ppm)	MgO per cent on a volatile-free basis	Source
Peridotite, Tonga Trench	3000	46.35	Engel and Fisher, 1969
Peridotites, mid-Atlantic ridge	1825	37.07	Gunn, 1976
Alkaline volcanics, E. Africa	200		Gerasimovsky, 1974
Picritic basalt, Hawaii	400	20.0	MacDonald, 1949
Picritic basalts, mid-Atlantic ridge	658	17.54	Gunn, 1976
Low Ti picritic basalts, mid-Atlantic ridge	357	11.75	Gunn, 1976
High Ti picritic basalts, mid-Atlantic ridge	274	10.37	Gunn, 1976
Olivine-poor basalts, Baffin Island	314	12.1	Clarke, 1970
Tholeiitic basalt, base of Karroo sequence, S. Africa	130	8.18	Cox and Hornung, 1966
Tholeiitic basalt, top of Karroo sequence	45	6.27	Cox and Hornung, 1966
Palaeozoic komatiitic basalts, Newfoundland	330	14.21	Gale, 1973
Precambrian greywacke, Canada	108		MacPherson, 1958
Devonian-Mississippian black shale, Kentucky	110		Connor and Shacklette, 1975
Non-carbonate sediments, East Pacific Rise	460		Cronan, 1976

Manganese nodules Pacifice Ocean	5837 (s = 3364)		Cronan, 1972
Manganese nodules, Australian region	4709 (s = 4219)		Noakes and Jones, 1975
Quartzo-feldspathic Lewisian gneiss	30		Bowes, 1978
METAMORPHOSED VOLCANIC ARCHAEAN ROCKS			
Canadian Shield basalt (205)	103	6.55	Baragar and Goodwin, 1969
Canadian Shield andesite (101)	63	3.90	Baragar and Goodwin, 1969
Canadian Shield salic volcanic (60)	24	1.83	Baragar and Goodwin, 1969
Abitibi, high-Mg basalt (3)	236	10.78	Gelinas and Brooks, 1974
Munro Township, average peridotite MgO >30 per cent	1571	33.6	Arndt and others, 1977
Munro Township, average peridotite MgO <30 per cent	785	26.5	Arndt and others, 1977
Belingwe, average peridotite	1328	26.5	Nisbet and others, 1977
Barberton, least altered peridotite	2120	32.97	Green and others, 1975
Barberton, average peridotite Sandspruit Formation (2)	1100	26.92	Viljoen and Viljoen, 1969
Barberton, average peridotite, Komati Formation (8)	1414	33.79	Viljoen and Viljoen, 1969
ARCHAEAN METASEDIMENTARY ROCKS			
Barberton, Sheba Formation greywackes	290		Condie and others, 1970
Barberton, Belvue Formation greywackes	160		Condie and others, 1970
Wyoming greywackes	91		Condie, 1967

Notes:

1. s = standard deviation.
2. number of samples shown in parentheses.

TABLE 6. AVERAGE ABUNDANCE AND RANGE OF SILICATE NICKEL AND MAGNESIA IN VARIOUS CLASSES OF METAMORPHOSED IGNEOUS ROCKS, YILGARN BLOCK

		Ni ppm			per cent MgO (volatile-free)		
	n	$\bar{x}$	s	Range	$\bar{x}$	s	Range
Olivine-rich ultramafic	52	2370	843	878-7000	40.6	4.27	36-52
Peridotite	72	1310	597	154-3600	30.9	2.19	28-36
Pyroxenite (picrite)	119	722	381	121-1560	21.2	4.06	15-28
Basalt (Mg-rich) and gabbroids	184	192	94	70-780	10.8	1.59	9-15
Total	414						

Notes:

1. Compilation of published and unpublished data (from various sources) by J A Hallberg (pers. comm., 1978). Analyzed rocks are from the Eastern Goldfields and Murchison Provinces.
2. Includes 91 gabbroids, pyroxenites, and harzburgites from layered sills.
3. Where analyzed, rocks containing more than 0.5 Wt per cent sulphur have been excluded.
4. n = number of samples; $\bar{x}$ = arithmetic mean; s = standard deviation.

Nickel is both a siderophile and chalcophile element (Goldschmidt, 1958). Siderophile elements will, in the presence of excess free iron, concentrate in the iron phase of meteorites and probably also in the supposed iron core of the earth. On the other hand chalcophile elements will, in the presence of sufficient sulphur without an excess of free iron, concentrate in sulphides. Therefore in crustal rocks nickel reaches its maximum abundance in sulphide mineral assemblages. In the absence of sulphur and free iron, nickel enters silicate minerals rich in magnesium, hence the relationship in Figure 7. Cobalt and the platinum-group metals behave in a similar way to nickel. The geochemical behaviour of nickel in crustal processes is discussed in detail later in the chapter.

IGNEOUS AND METAMORPHIC PETROLOGY OF ULTRAMAFIC ROCKS

IGNEOUS PETROLOGY

Ultramafic rocks are defined as those containing more than 90 per cent mafic igneous minerals (olivine, pyroxene, amphibole) and/or their metamorphic mineral derivatives. Mafic rocks contain between 65 and 90 per cent mafic minerals (Streckeisen, 1973). The chief felsic igneous mineral involved in making up the total percentage is calcic plagioclase. The term ultramafic is preferred over the term ultrabasic which can only be applied to analyzed rocks that contain less than 45 weight per cent silica, not all of which are necessarily ultramafic. Many pyroxenites are not ultrabasic whereas nephelinites, carbonatites and some anorthosites are ultrabasic.

Classification of ultramafic and related mafic igneous rocks is summarized in Figure 8. The system closely follows that recommended by Streckeisen (1973), with additional subdivision of the olivine-rich ultramafics because these rocks are the most important ones in relation to nickel. The modal content of the primary igneous olivine, clinopyroxene, orthopyroxene and plagioclase forms the basis of the system. In addition the magnesia content (calculated on a volatile-free basis) is used, as most of the ultramafic rocks in question consist of metamorphic minerals, although pseudomorphic textures may allow reasonable estimates of the primary mineralogy to be made (e.g. Williams, 1971).

Viljoen and Viljoen (1969) introduced the term 'komatiite' to describe a suite of metamorphosed Archaean lavas ranging in composition from basalt to peridotite, which occur in the Barberton Mountain Land of South Africa. Characteristic chemical features such as high silica, low alkali elements, high $CaO{:}Al_2O_3$ and high Fe:Mg were considered important in distinguishing komatiites from other classes of mafic-ultramafic igneous rocks. Komatiites have subsequently been described from most Archaean terrains, but various modifications (e.g. Naldrett, 1971; Nesbitt and Sun, 1976; Arndt and others, 1977) to the original chemically-oriented definition have been proposed to accommodate regional differences. Furthermore there is general agreement that textural evidence (e.g. spinifex textures and skeletal crystals or glass) for the existence of komatiites as magnesia-rich extrusive liquids is important in characterizing the rock suite in general (e.g. Nesbitt, 1971; Williams, 1972; Brooks and Hart, 1974; Nisbet and others, 1977; Arndt and others, 1979). However, this is complicated

TABLE 7. AVERAGE ABUNDANCE OF SILICATE NICKEL AND MAGNESIA IN VARIOUS METAMORPHIC ROCKS FROM THE PILBARA AND YILGARN BLOCKS

		Ni (ppm)		MgO per cent volatile free (%)		
	n	$\bar{x}$	s	$\bar{x}$	s	Source
GRANITOID ROCKS						
Rason, Laverton, Leonora 1:250 000 sheet areas	252	28	17			Davy, 1976
Marda complex	5	10				Hallberg and others, 1976
pre- and syntectonic granitoids, Pilbara Block	29	19	15			Hickman, in press
porphyritic granitoids, Pilbara block	12	15	4			Hickman, in press
post-tectonic granitoids, Pilbara Block	7	13	3			Hickman, in press
FELSIC SUPRACRUSTAL ROCKS						
felsic volcanics, Pilbara	107	18	13			Hickman, in press
felsic volcanics, Duffer Formation, Pilbara	82	25	9			Hickman, in press
felsic volcanics, Wyman Formation, Pilbara	25	4	2			Hickman, in press
felsic volcanics, Marda	4	5				Hallberg and others, 1976
arkose, Jones Creek	6	10	8			Marston, 1978
BASALTIC ROCKS						
basalt, Pilbara	279	108	38			Hickman, in press
N. Star Basalt, Pilbara	80	72		7.11		Hickman, in press
Mt Ada Basalt, Pilbara	69	79		6.88		Hickman, in press
Apex Basalt, Pilbara	53	167		8.89		Hickman, in press
Euro Basalt, Pilbara	16	113		7.37		Hickman, in press
Charteris Basalt, Pilbara	26	136		8.20		Hickman, in press
Honeyeater Basalt, Pilbara	35	81		8.14		Hickman, in press
komatiitic basalt, Pilbara	20	273	70	13.44		Hickman, in press
high-Mg basalt, Meekatharra area	4	228	84	12.46	1.56	Hallberg and others, 1976
high-Mg basalt, Mt Monger	4	330	123	13.67	0.68	Williams, 1971
high-Mg basalt, Mt Monger	3	197	130	9.74	0.49	Williams, 1971
high-Mg basalt, Mt Monger	4	164	117	7.65	0.69	Williams, 1971
basalt, Lawlers-Mt Goode	9	97	37	6.80	0.23	Naldrett and Turner, 1977
tholeiite, Mt White-Lawlers	4	60	4	6.52	0.19	Nesbitt and Sun, 1976
basalt, Mt White-Lawlers	4	87	8	6.77	0.07	Nesbitt and Sun, 1976
high-Mg basalt, Mt White-Lawlers	4	260	59	12.60	0.70	Nesbitt and Sun, 1976
basalt, Kalgoorlie-Norseman	123	161	26	6.80	0.90	Hallberg, 1972
basalt, Mt Hunt	5	243		10.02		Hallberg, 1972a
PYROXENITIC VOLCANIC OR SUBVOLCANIC ROCKS						
tremolite-chlorite schist, Yakabindie	3	454	102	15.20	0.85	Naldrett and Turner, 1977
high-Mg basalt, Mt Monger	3	706	403	18.72	2.67	Williams, 1971
tremolite-chlorite rock, Yakabindie	5	1089	245	23.36	3.50	Naldrett and Turner, 1977
tremolite-chlorite rock, Kambalda	14	1116	238	23.44	0.72	Ross and Hopkins, 1975
chlorite-tremolite rock, marginal to leases, Mt Hogan	10	1339	86	24.90	1.19	Williams, 1971
tremolite-chlorite, Nepean	2	940	113	23.14	0.08	Barrett and others, 1976
PERIDOTITIC VOLCANIC OR SUBVOLCANIC ROCKS						
spinifex peridotite, Ruth Well	2	1288	150	28.42	0.57	Keeley, 1974
peridotite, Pilbara	5	1435		34.11		Hickman, in press
spinifex peridotite, Mt Burges	3	1449	160	29.48	1.12	Nesbitt and Sun, 1976
talc-chlorite-dolomite, Kambalda	33	1796	577	30.96	3.33	Ross and Hopkins, 1975
talc-carbonate-serpentinite Windarra	2	1900		36.0		Groves and Hudson, 1981
spinifex talc-carbonate-chlorite-serpentinite Windarra	3	1700		30.9		Groves and Hudson, 1981
peridotite, cores of lenses, Mt Hogan	14	1963		33.3		Williams, 1972
spinifex peridotite, Scotia	1	1562		31.94		Nesbitt and Sun, 1976
peridotite, Yakabindie	4	1995	106	34.22	1.15	Naldrett and Turner, 1977
tremolite-chlorite-olivine, Nepean	4	1670	150	29.41	0.90	Barrett and others, 1976
tremolite-chlorite-carbonate-serpentinite Windarra	5	1750		29.9		Groves and Hudson, 1979
OLIVINE-RICH VOLCANICS OR SUBVOLCANIC ROCKS						
talc-carbonate-chlorite, Kambalda	12	2578	1724	36.97	109	Ross and Hopkins, 1975
talc-magnesite-chlorite, and serpentinite, Kambalda	12	2710	432	42.70	0.82	Ross and Hopkins, 1975
serpentine-chlorite-talc, Nepean	4	2875	200	44.51	1.82	Barrett and others, 1976
serpentine and talc-carbonate, Windarra	7	2500		38.8		Groves and Hudson, 1979
talc-carbonate-olivine, Mt Edwards	1	2800		39.9		INAL staff, 1975
OLIVINE RICH INTRUSIVE ULTRAMAFIC ROCKS						
serpentinite and talc-carbonate, Black Swan	4	3590	740	46.31	2.25	AMIRA project (unpublished data)
serpentine, Mt Hope	3	3855	210	49.40	0.53	AMIRA project (unpublished data)
dunite, Cosmic Boy	10	3541	1572	46.47	1.66	AMIRA project (unpublished data)
serpentinite, Wiluna	8	3092	523	48.32	0.90	AMIRA project (unpublished data)
serpentinite and talc-carbonate, Mt Keith	8	3633	685	48.99	2.63	AMIRA project (unpublished data)
talc-carbonate, Mt Keith	2	3335	426	38.39	1.82	AMIRA project (unpublished data)
ROCKS FROM LAYERED SILLS						
peridotite, Mt Monger	7	970		31.1		Williams and Hallberg, 1973
orthopyroxenite, Mt Monger	2	320		23.1		Williams and Hallberg, 1973
norite, Mt Monger	8	159		12.4		Williams and Hallberg, 1973
norite-gabbro, Mt Monger	6	129		8.9		Williams and Hallberg, 1973
gabbro, Mt Monger	1	61		6.2		Williams and Hallberg, 1973
ultramafic zone, Munni Munni	7	714	194	19.11	2.45	Donaldson, 1974
gabbro zone, Munni Munni	4	130	65	5.83	1.35	Donaldson, 1974
bronzitite, Mission Sill	6	375	47	24.95	1.53	McCall, 1973
harzburgite, E. Goldfields	27	931	153	30.11	2.52	Hallberg, (unpublished data)

n = number of samples
$\bar{x}$ = arithmetic mean
s = standard deviation
AMIRA = Australian Mineral Industries Research Association

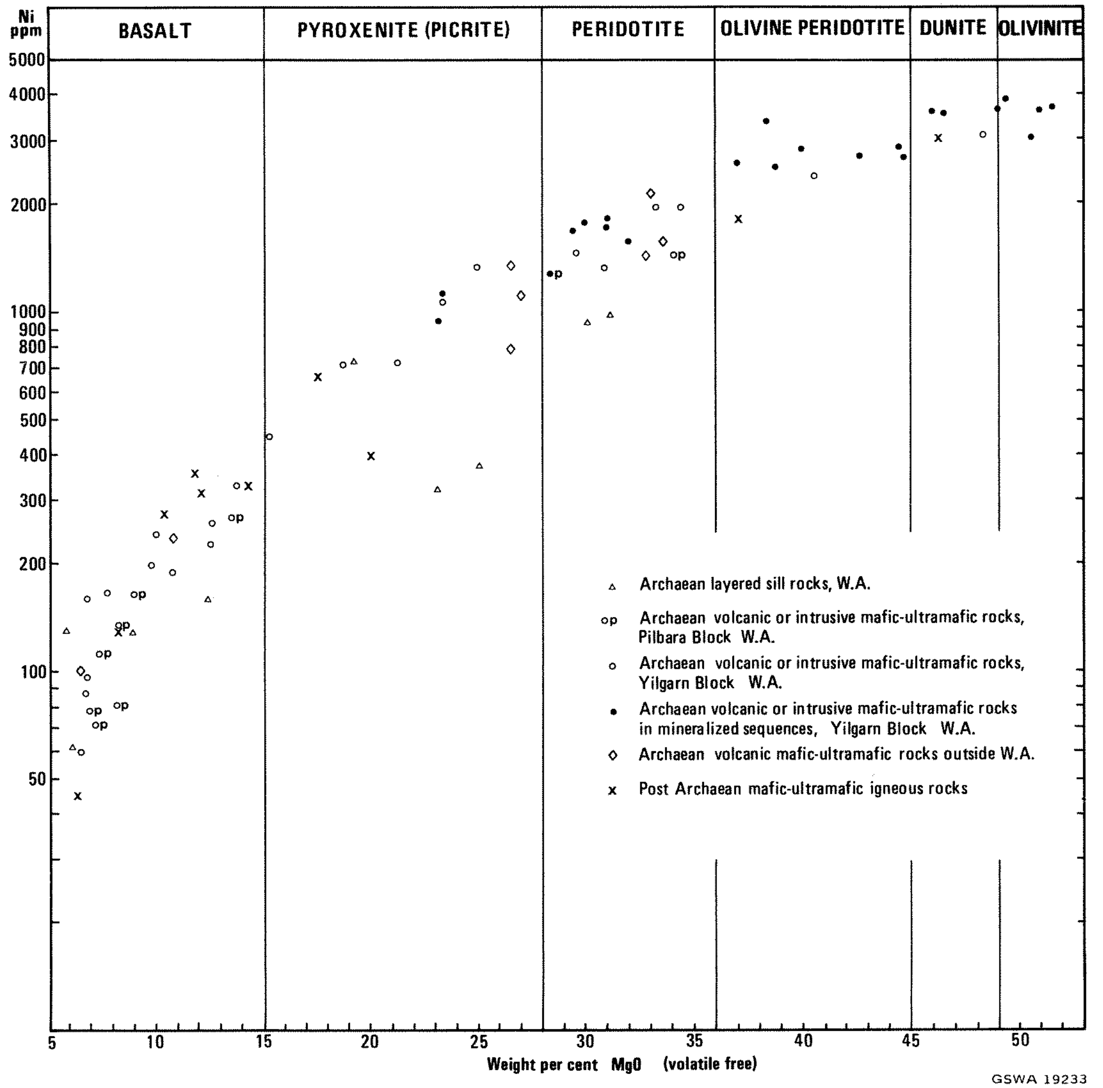


Figure 7. Nickel versus magnesia plot for mafic-ultramafic igneous rocks from Western Australia and other areas (data from Tables 6 and 7).

by the occurence of spinifex textures in rocks of low magnesia and high silica contents, which could be regarded as andesites (Arndt and others, 1977, p.346). Using rare earth element geochemistry, Sun and Nesbitt (1978) concluded that komatiitic basalts (in the sense of Viljoen and Viljoen, 1969) were not related to komatiitic peridotites by processes of crystal fractionation as previously assumed by several earlier workers. In addition they only recognized the term komatiitic as applied in high magnesia (20 per cent) rocks with distinctive textural and field characteristics.

There are major difficulties now in using komatiite as a *rock* term (e.g. basaltic or peridotitic komatiite) especially in the case of basalts. The thick "footwall basalt" underlying the ultramafic sequence of Kambalda has been variously regarded as tholeiite (Ross and Hopkins, 1975), komatiite (Naldrett and Turner, 1977), and as a rock with a rare earth element pattern resembling both tholeiite and "depleted basalt" with 12 per cent magnesia (Sun and Nesbitt, 1978). Accordingly, in this bulletin komatiite will only be used in its adjectival form (komatiitic) to refer to the probable petrological affinities of rocks or rock sequences, based on the presence of textures and chemistry which demonstrate derivation from magnesia-rich volcanic liquids.

METAMORPHIC PETROLOGY

The metamorphic petrology of ultramafic rocks in the State is complex (Table 8). The main factors responsible for this complexity are:

(i) a wide range of original igneous compositions;

(ii) the incomplete replacement of igneous minerals by metamorphic minerals during prograde metamorphism;

(iii) the partial superimposition of retrograde metamorphic minerals on prograde assemblages;

(iv) talc-carbonate alteration of earlier metamorphic assembalges.

TABLE 8. VARIATION IN RELICT IGNEOUS AND METAMORPHIC MINERALOGY IN ULTRAMAFIC ROCKS WITH METAMORPHIC GRADE

Metamorpic grade and metamorphic facies	Very low Prehnite-pumpellyite and lower greenschist	Low Mid-greenschist and greenschist-amphibolite transition	Medium Low amphibolite	High Mid-high amphibolite
A. RELICT MINERALOGY				
glass	———	———	——	
calcic plagioclase +	———	———	——	
orthopyroxene +	———	———	——	
clinopyroxene	———	———	——	
chromite	———	———	—— modified ——	——
olivine (forsterite)			———	———
B. METAMORPHIC MINERALOGY				
brucite*	———			
pyroaurite-stichtite*	———	———		
lizardite	———	———		
magnetite	———	———		
magnesite	———	———	———	———
dolomite	———	———	———	———
chlorite	———	———	———	———
tremolite-actinolite	———	———	———	———
antigorite		——	———	——
chromian magnetite		——	———	———
talc		———	———	———
olivine (forsterite)			———	———
chromite			———	———
anthophyllite				———
enstatite				——
spinel				——
albite†		———	——	
quartz†		———	——	

* confined to metadunite + mainly confined to layered sills † restricted to carbonated pyroxenitic rocks

Data modified after Groves and Hudson (1981).

TABLE 9. VARIATION IN METAMORPHIC ASSEMBLAGES WITH BULK COMPOSITION AND NATURE OF METAMORPHISM—ULTRAMAFIC ROCKS AT KAMBALDA

Class \ Nature of metamorphic alteration	Partly altered (rare)	Altered but not carbonated	Partly carbonated	Intensely carbonated
Olivine-rich ultra-mafics (›36% MgO)	Relict ol-lizardite	antig + chl	tc-antig-ms-dol-chl	tc-ms + chl ∓ dol tc-ms-chl ∓ dol
Peridotites (28-36% MgO)	Relict ol-trem-chl-tc relict ol-trem-chl	antig-trem-chl ∓ tc trem-antig-chl	tc-dol-ms-chl tc-dol-chl tc-chl-trem-dol	tc-dol-ch ∓ ms tc-chl-dol-qtz ∓ ms
Pyroxenites (Picrites) (15-28% MgO)		trem-chl ∓ antig trem-chl-plag (epidote)	trem-chl-tc ∓ dol trem-chl ∓ dol	trem-chl-tc-dol-qtz ∓ plag chl-dol-qtz + plag ∓ tc

antig: antigorite chl: chlorite dol: dolomite ms: magnesite ol: olivine plag: plagioclase qtz: quartz tc: talc trem: tremolite

Notes:

1. Minerals in each assemblage arranged in order of decreasing amount.
2. Assemblages in each class arranged in order of decreasing magnesia content.
3. Based on Bavinton (1979).

Binns and others (1976) described complex metamorphic assemblages and their distribution in the eastern Yilgarn Block and discussed the significance of relict igneous olivine and clinopyroxene. Their data form the basis for Table 8. The influence of factors (i), (ii) and (iv) on ultramafic petrology is illustrated by Table 9, which uses the ultramafic sequence at Kambalda as a model. This sequence underwent regional metamorphism which attained a maximum temperature of 510°C ∓ 20°C at 250MPa ∓ 100MPa (Bavinton, 1979), conditions corresponding to the greenschist-amphibolite facies boundary.

In addition to the mineralogical variations referred to above, there is a complex array of textures present in ultramafic rocks. These textures can be grouped into the following five types (Fig. 9) which will be used when describing the deposits later. These types are:

1. *static igneous texture* in which the shapes and inter-relationships of igneous minerals are preserved undeformed by pseudomorphic metamorphic minerals (e.g. spinifex-textured tremolite-chlorite rock);
2. *dynamic igneous texture* is the equivalent of 1 but in the deformed (e.g. sheared or flattened) condition;
3. *static metamorphic texture* is a random growth of metamorphic minerals which compeltely replaces or obscures any igneous texture (e.g. bladed olivine-talc rock, rosetted tremolite-chlorite rock);
4. *dynamic metamorphic texture* is the equivalent of 3 but in a deformed condition;
5. *overprint texture* is an incomplete super-imposition of metamorphic porphyroblasts over textures 1, 2 or 4 (e.g. porphyroblastic olivine in a spinifex-textured tremolite-chlorite rock), or it may refer to the patchy development of 3 in 1 (e.g. patches of bladed olivine-talc rock in a granular serpentinite).

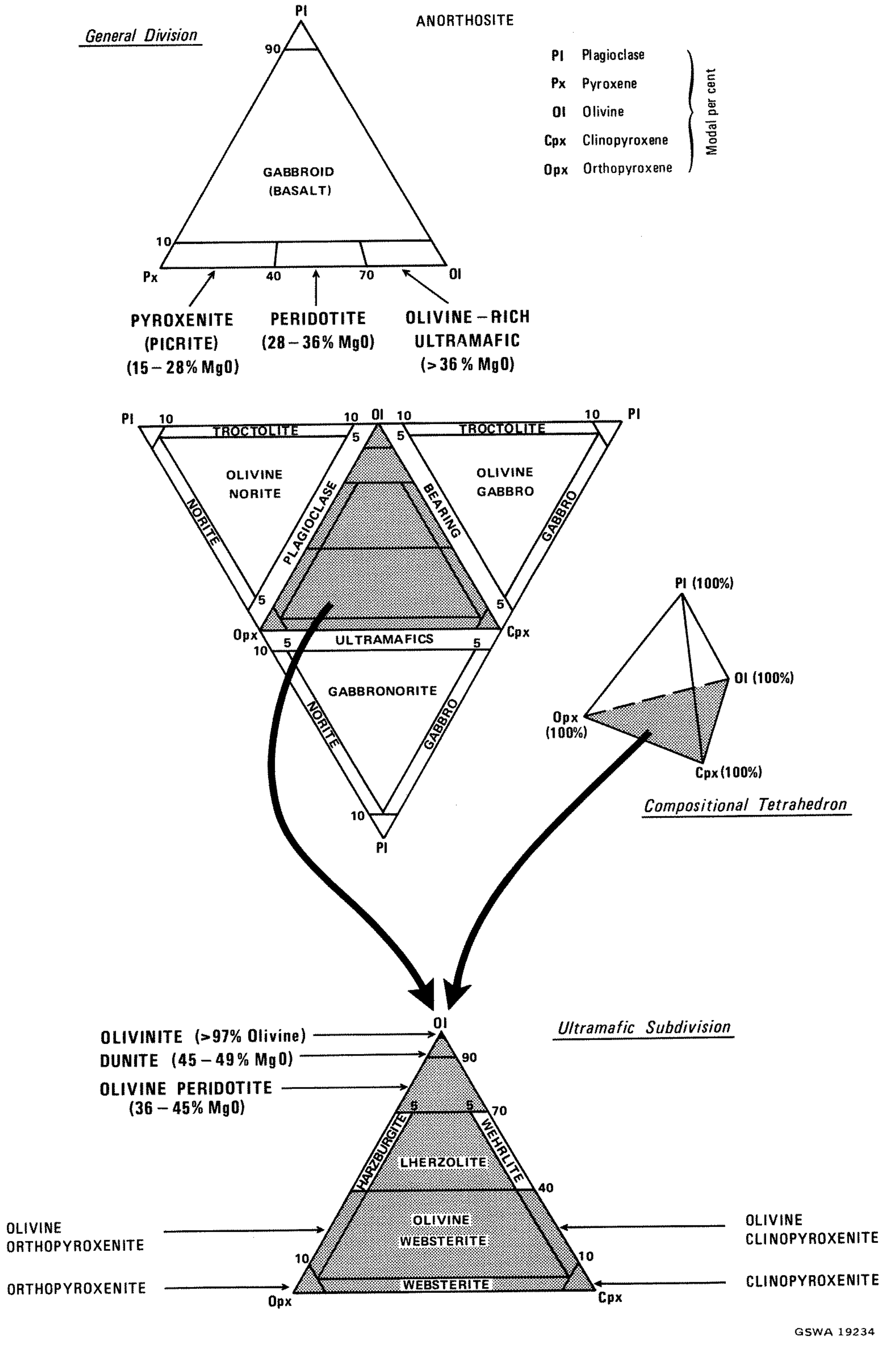


Figure 8. Classification and nomenclature of ultramafic and related mafic rocks in the tetrahedron plagioclase-orthopyroxene-clinopyroxene-olivine, as used in the bulletin.

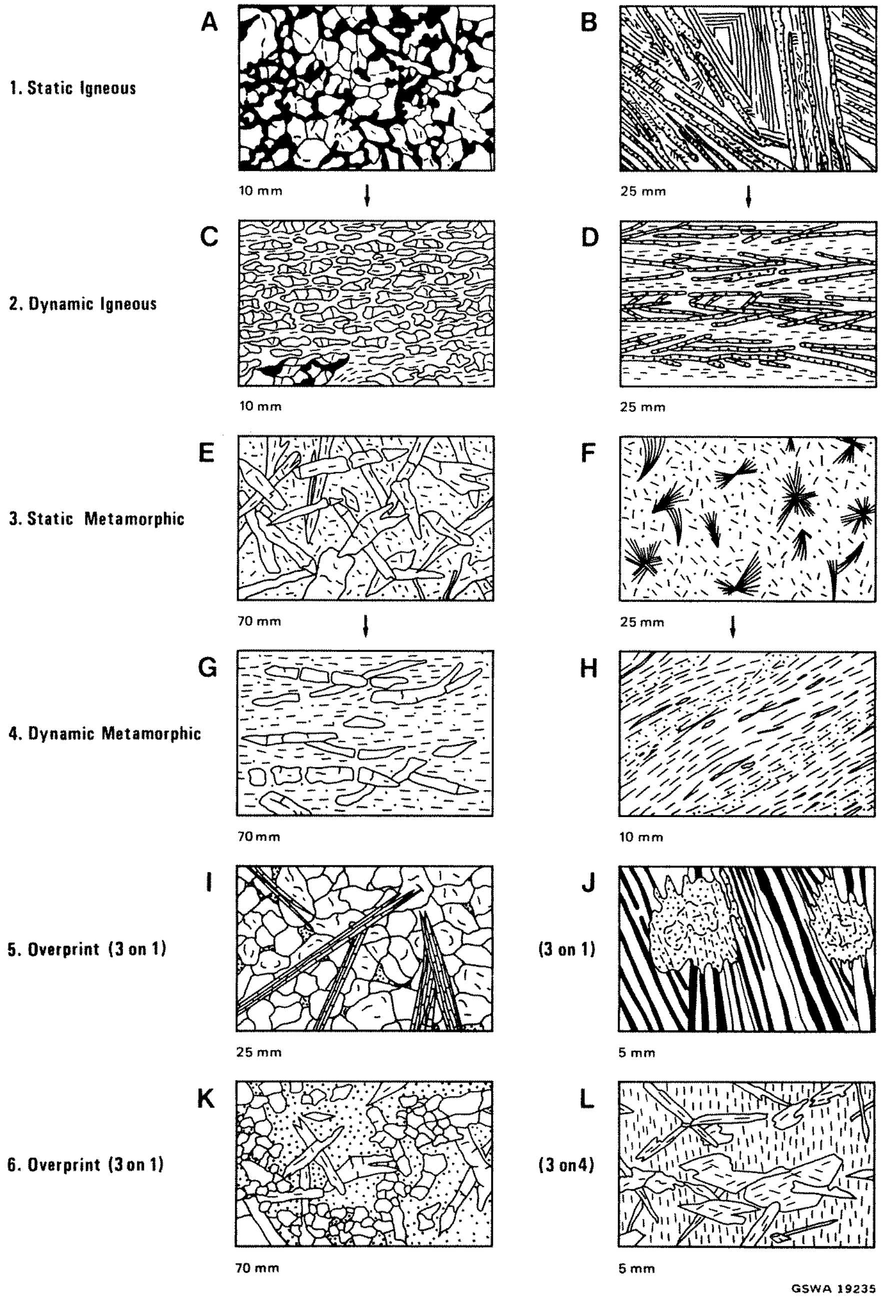


Figure 9. Textural types in ultramafic rocks.

(A) Subequant serpentinized olivine grains (white) enclosed in a fine-grained chloritic (devitrified glass) matrix (black); peridotitic rock from the basal (B) zone of an ultramafic flow.

(B) Serpentinized olivine platelets (stippled) and smaller, thinner tremolite platelets defining a platy spinifex texture in a pyroxenitic rock from the upper (A) zone of an ultramafic flow.

(C) Deformed version of (A) with lensoid antigorite grains in a foliated chloritic matrix. A relict of the original texture is preserved in the lower left of the sketch.

(D) Deformed version of (B).

(E) Interlocking bladed metamorphic olivine (serpentinized) in a matrix of talc and tremolite. Peridotite from a high grade terrain.

(F) Rosettes and fan-like aggregates of tremolite in a fine-grained tremolite-chlorite matrix. Pyroxenite from a medium grade terrain.

(G) Deformed version of (E), a serpentine-talc-tremolite schist.

(H) Deformed version of (F), a tremolite-chlorite schist.

(I) Coarse porphyroblastic blades of anthophyllite superimposed on a close-packed aggregate of subequant serpentinized igneous olivine grains with a little interstitial talc and chlorite. Dunitic rock from a high grade terrain.

(J) Irregular porphyroblastic olivine (stippled) superimposed on lamellae of tremolite (dark) and chlorite (white) defining an original platy spinifex texture. Note preferential replacement of tremolite. Pyroxenitic rock from a high grade terrain.

(K) Incomplete replacement of a close-packed, subequant olivine texture by bladed metamorphic olivine in a matrix of talc, tremolite and chlorite. Both types of olivine are serpentinized.

(L) Coarse porphyroblastic tremolite prisms superimposed on a fine-grained chlorite-tremolite matrix with well developed schistosity.

Approximate widths of fields of view are indicated in millimetres.

This scheme is an extension of that proposed by Binns and others (1976, p.306) to describe two contrasting styles of metamorphism at the regional scale in the eastern Yilgarn Block. Their "static-style" metamorphism is characterized by preservation of primary textures and a lack of mineral orientation and penetrative tectonic fabrics, except in incompetent rocks. Metamorphic grade generally falls in the range from very low to medium. On the other hand their "dynamic-style" metamorphism is typified by the obliteration of most original textures and the presence of penetrative foliation and lineation. Metamorphic grade is generally medium to high.

The igneous textures are best known (e.g. Fig. 9 A and B) and have been described from Archaean terrains in Australia, southern Africa and Canada. An understanding of the metamorphic textures present is comparatively recent particularly with respect to the recognition of metamorphically generated olivine crystals (Fig. 9 E and J) in pyroxenitic to dunitic ultramafics (Oliver and others, 1972) and their distinction from relict igneous olivines (Binns and others, 1976). This distinction is readily made on textural grounds in some cases (e.g. Fig. 9A and B versus 9E), but elsewhere coarse radiating spinifex textures (e.g. Nesbitt 1971, Plate 12b) may resemble bladed metamorphic olivine textures. In some rocks, if the olivine is not completely serpentinized, relict igneous olivines are commonly brownish in colour with abundant minute opaque inclusions, whereas metamorphic olivines are generally colourless (Binns and others, 1976). Colourless rims on brown cores (e.g. Martin and Allchurch, 1975) may indicate the arrested direct replacement of igneous by metamorphic olivine. However, elsewhere metamorphic olivine appears to have grown at the expense of serpentine minerals themselves derived from the partial or complete metamorphic hydration of igneous olivine (e.g. Barrett and others, 1976). Electron microprobe studies indicate that in ultramafic rocks of equivalent bulk composition igneous olivine is more magnesian and nickel-rich than metamorphic olivine (Groves and Hudson, 1981). At Kambalda, for example, reddish brown relict igneous olivine contains 2 000 to 4 500 ppm nickel, whereas pale to colourless metamorphic olivine contains 850 to 1 200 ppm nickel (Bavinton, 1979).

Most olivine, whether igneous or metamorphic, is affected to some degree by serpentinization. In medium- to high-grade terrains this alteration is commonly retrograde as olivine is replaced by lizardite, a serpentine mineral generally stable below 200 to 250°C. Chlorite or talc are also found retrogressively replacing high grade metamorphic minerals such as enstatite and anthophyllite (e.g. Barrett and others, 1976). In many areas there is clear textural evidence that the carbon dioxide metasomatism responsible for producing talc-carbonate assemblages in ultramafic rocks was superimposed on earlier metamorphic assemblages. This alteration is therefore generally retrograde in character also, and it commonly results in the obliteration of earlier textures. Where alteration is complete in rocks of olivine-rich ultramafic composition, a representative end product consists of porphyroblastic rhombs of magnesite set in a matrix of talc plus minor chlorite and dolomite (*cf.* Table 9).

Both prograde and retrograde metamorphic processes have important effects on the sulphide-oxide minerals in ultramafic rocks. These effects are discussed later in the chapter.

TABLE 10. MINERALOGY OF NICKEL SULPHIDE DEPOSITS IN WESTERN AUSTRALIA, EXCLUDING SILICATE MINERALS

Mineral Group \ Alteration Zone	Primary zone	Supergene zones	Oxide zone
Native elements	Awaruite, Nickel, Bismuth, Carbon, Copper,	Copper, Gold	Copper, Gold
Oxides	FERROCHROMITE, MAGNETITE, Ilmenite, Pyrophanite, Rutile, Spinel, Tervorite	Magnetite	GOETHITE, haematite, magnetite, cryptomelane
Sulphides	CHALCOPYRITE, PENTLANDITE, PYRITE, PYRRHOTITE, Argentian Pentlandite, Bismuthinite, Bornite, Bravoite, Chalcocite, Cinnabar, Cubanite, "Chalcopentlandite", Galena, Godlevskite, Heazlewoodite, Joseite A, Mackinawite, Millerite, Molybdenite, Parkerite, Polydymite, Siegenite, Sphalerite, Troilite, Vaesite, Valleriite, Violarite	Carrollite, Chalcocite, Chalcopyrite, Covellite, Greigite, MARCASITE, Millerite, PYRITE, Smythite, Valleriite, VIOLARITE	CARBONATES AND HYDROCARBONATES Calcite, Carrboydite, Gaspeite, Glaukosphaerite, MAGNESITE, Malachite, Nickeloan para-atacamite Otwayite, Reevesite, SIDERITE, Takovite
Tellurides	Altaite, Calaverite, Hessite, Melonite, Michenerite, Rucklidgeite, Tellurobismuthite, Testibiopalladite, Volynskite	SULPHATES/HYDRATES Morenosite, Nickelblodite, Nickelheahydrate, Retgersite	
Arsenides and antimonides	Arsenopyrite, Cobaltite, Gersdorffite, Maucherite, Niccolite, Skutterudite, Sperrylite, Stibnite, Ullmanite		
Carbonates	DOLOMITE, MAGNESITE, Calcite	Dolomite, MAGNESITE, SIDERITE	

Notes:

1. Common minerals are shown in capitals.
2. Minerals containing large amounts of nickel are underscored with a full line.
3. Minerals containing small or trace amounts of nickel are underscored with a broken line.
4. Based on Groves and Hudson (1981) with additions.

MINERALOGY AND PHASE EQUILIBRIA

The non-silicate mineralogy of nickel deposits is summarized in Table 10 which shows variations caused by oxidation and supergene alteration of primary assemblages. Nickel-bearing minerals are detailed in Table 11. Hydrous nickeliferous silicates are found both in the oxide and supergene zones of sulphide deposits and in lateritic nickel deposits. These minerals are essentially the nickel-bearing analogues of familiar magnesium silicates, with, in most cases, continuous substitution of nickel for magnesium resulting in a wide range of compositions (Table 12). Brindley and Maksimovic (1974) recommended that the name "garnierite" be used only as a field term, before more sepcific identification. They also suggested that terms such as 7 Å (0.7nm) (serpentine-like) and 10 Å (0.10nm) (talc-like) garnierite are useful when identification can proceed no further than recognition of basal chrystallographic spacings (measured by X-ray diffraction).

The common primary sulphide minerals in Western Australian deposits are pentlandite, pyrrhotite, pyrite and chalcopyrite. Sulphides more nickeliferous than pentlandite, and nickel arsenides are rare. The other primary nickel minerals (Table 10) are of mineralogical interest only. All these sulphide minerals are unstable in the presence of oxygen or oxygenated groundwaters, and oxidation converts them to supergene (secondary) minerals and eventually to iron oxides and hydroxides. The oxides are generally the surface expression of mineralization and are known as gossans. Supergene processes are discussed at the end of the chapter.

The common primary sulphide minerals are accompanied by magnetite and ferrochromite. Accordingly, most natural nickel sulphide ores have mineral phases whose compositions can be represented by the system Fe-Ni-Cu-S-O with cobalt and chromium as additional minor components. The application of experimentally determined phase relations within this system helps to explain the mineralogy of natural ores and the crystallization history of sulphide liquids. Furthermore, as all nickel sulphide assemblages in the State have been metamorphosed, the lower temperature phase equilibria are of particular importance as metamorphic cooling was probably more prolonged than the magmatic cooling of sulphide liquids (over the relevent temperature interval). Some of the important contributions to our knowledge of the experimental systems are by Craig and Kullerud (1969), Naldrett (1969), Shewman and Clarke (1970), Barton (1973), and Ewers and others (1976). Craig and Scott (1974) provided a useful summary of phase equilibria in the component binary and ternary metal-sulphur systems.

The compositions of pyrrhotite, pentlandite and pyrite all fall within the Fe-Ni-S system (Fig. 10) which is well understood at all except the lowest temperatures. At high temperatures (about 1150°C) molten sulphide liquids first crystallize an iron-rich, pyrrhotite-like solid solution phase known as monosulphide solid solution (mss). Oxygen dissolves in sulphide melts and depresses the temperature

TABLE 12. HYDROUS NICKELIFEROUS SILICATES

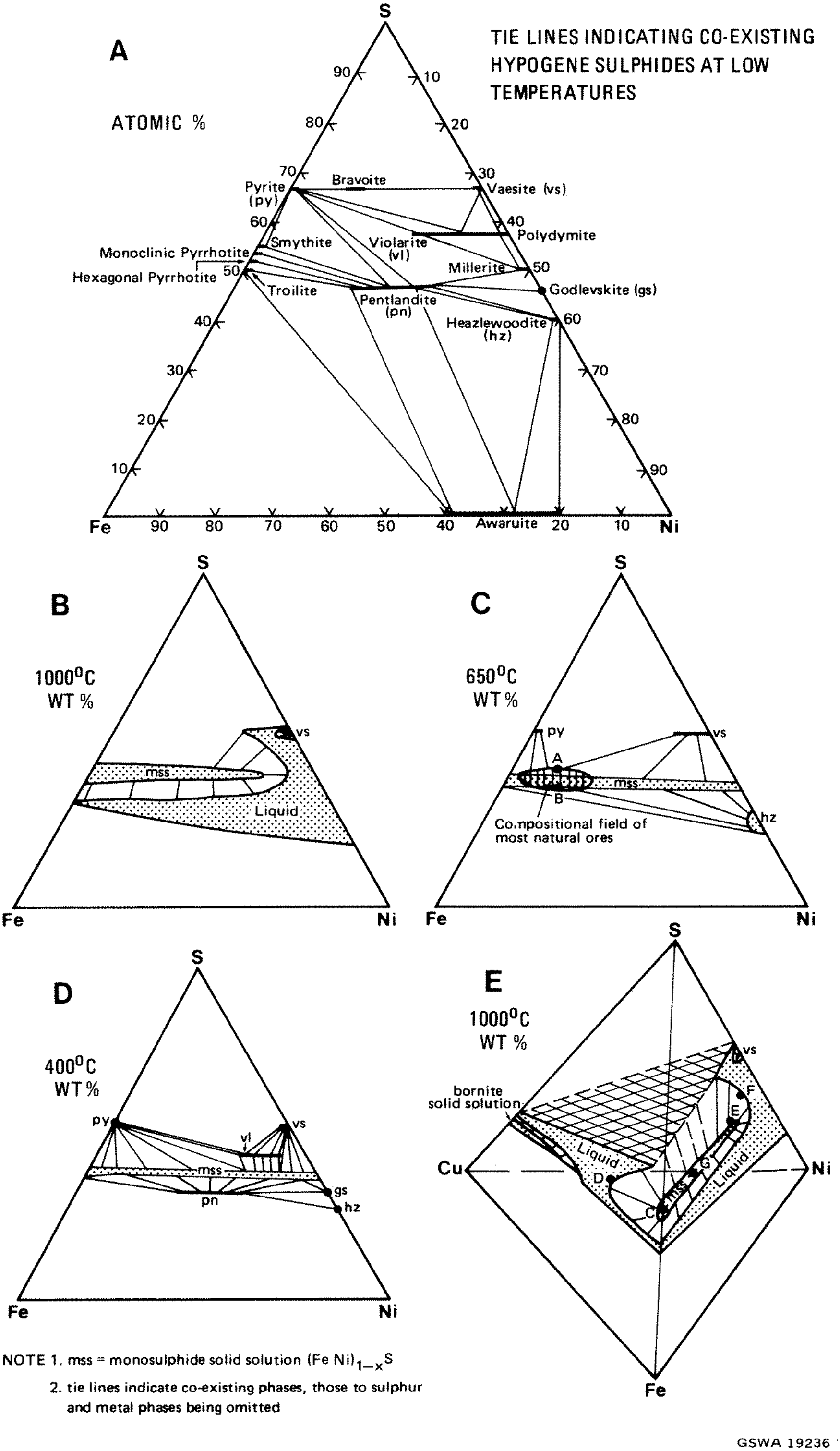
SERPENTINE GROUP MINERALS	
Chrysotile → $Mg_3Si_2O_5(OH)_4$	Pecoraite series (up to 46) $Ni_3Si_2O_5(OH)_4$
Lizardite → $Mg_3Si_2O_5(OH)_4$	Nepouite series (25-40) $(Ni,Mg)_3Si_2O_5(OH)_4$
Berthierine → $(FeMg)_2(Si,Al)O_5(OH)_4$	Brindleyite series (up to 11) $(Ni,Al)_{3.0}(Si,Al)O_5(OH)_4$
TALC AND TALC—LIKE MINERALS	
Talc → $Mg_6Si_8O_{20}(OH)_4$	Willemseite series (up to 27) $(Ni_{4.2}Mg_{1.6}Fe_{0.2})Si_8O_{20}(OH)_4$
Kerolite → $Mg_6Si_8O_2(OH)_4$	Pimelite series (up to 35) $(Ni,Mg)_6Si_8O_{20}(OH)_4$
CHLORITE AND CHLORITE-LIKE MINERALS	
Chlorite (Clinochlore) → $(Mg,Al,Fe)_{12}(Si,Al)_8O_{20}(OH)_{16}$	Nimite series (10-25) $Ni_{5.5}Mg_{3.5}Al_2Fe)(Si,Al)_8O_{20}(OH)_{16}$
CLAY-LIKE MINERALS	
Nickeliferous Sepiolite → $(Ni,Mg)_3Si_4O_{11}.nH_2O$ (falcondoite)	Nickeliferous Montmorillonites (smectites) $Na_{0.5}(Al,Mg,Ni)_4Si_8O_{20}(OH)_4.nH_2O$ (with Fe added = nontronite)

Notes:

1. Approximate weight per cent Ni content shown in parenthesis.
2. After Brindley and Maksimovic, 1974; and Brindley, 1978.

TABLE 11. NICKELIFEROUS MINERALS (EXCLUDING SILICATES) IN NICKEL SULPHIDE DEPOSITS IN WESTERN AUSTRALIA

Mineral	Ideal formula	Wt%Ni	Mean Specific Gravity	Mineral	Ideal formula	Wt%Ni	Mean Specific Gravity
Awaruite	$FeNi_2$	68	8	Nickelhexahydrate	$NiSO_4.6H_2O$		
Bravoite	$(FeNiCo)S_2$	ca 25	4.5	Nickeloan para-atacamite	$(Cu,Ni)_2OH_3Cl$		
Carroboydite	$(Ni,Cu)_7Al_{4.5}(SO_4,CO_3)_{2.8}(OH)_{21.7}3.7H_2O$	30	2.5	Otwayite	$(Ni,Mg)_2(OH)_2CO_3.H_2O$	49	3.41
Gaspeite	$(MgNi)CO_3$	ca.40		Parkerite	$Ni_3Bi_2S_2$	27	8.4
Gersdorffite	NiAsS	35	5.9	Pentlandite	$(Fe,Ni)_9S_8$	25-44	4.96
Glaukosphaerite	$(Cu,Ni)_2(OH)_2CO_3$	9-22	3.9	Polydymite	Ni_3S_4	58	4.7
Godlevskite	Ni_7S_6	68		Reevesite	$Ni_6Fe_2(OH)_{16}CO_3.4H_2O$	ca.35	
Heazlewoodite	Ni_3S_2	73	5.82	Retgersite	$NiSO_4.6H_2O$		2.04
Maucherite	$Ni_{11}As_8$	52	7.80	Siegenite	$(Co,Ni)_3S_4$	ca.29	4.65
Melonite	$NiTe_2$	19	7.35	Skutterudite	$(Co,Ni)As_3$		6.5
Millerite	NiS	65	5.5	Takovite	$Ni_5Al_4O_2(OH\text{-}CO_3)_{18}.6H_2O$		
Morenosite	$NiSO_4.7H_2O$		1.95	Trevorite	$NiFe_2O_4$		5.16
Niccolite	NiAs	44	7.78	Ullmanite	NiSbS	28	6.65
Nickel	Ni	100	8.91	Vaesite	NiS_2	48	4.28
Nickelblodite	$Na_2Ni(SO_4)_2.4H_2O$	8-13	2.43	Violarite	$FeNi_2S_4$	30-54	4.65



NOTE 1. mss = monosulphide solid solution (Fe Ni)$_{1-x}$S

2. tie lines indicate co-existing phases, those to sulphur and metal phases being omitted

Figure 10. Phase relations in the Fe-Ni-S and Fe-Ni-Cu-S systems at various temperatures.

at which mss separates by 50 to 100°C: magnetite and ferrochromite crystallize later from the residual liquid which became enriched in oxygen as mss crystallized. On cooling, the mss progressively contains more nickel (thus depleting the residual liquid in nickel) until its composition spans the Fe-Ni-S system from $Fe_{1-x}S$ to $Ni_{1-x}S$ at 900°C (Fig. 10). The mss can accomodate copper (Fig.10E) and cobalt into its structure. Little change takes place in mss on further cooling (Fig.10C and D) until below 300°C when it breaks down into the component phases.

Either pyrite or pentlandite may begin to crystallize at about 600°C if the bulk composition of the ore (and hence mss) is adjacent to the sulphur-rich (point A, Fig.10C) or sulphur-poor (point B) limits of mss. For most ores, a chalcopyrite-like phase ($CuFeS_2$) would also be crystallizing at these temperatures, although some copper can be taken into solid solution in pentlandite. This chalcopyrite would probably be in equilibrium with a Cu-Fe-S intermediate solid solution (iss), which at lower temperatures would break down to chalcopyrite and pyrite.

If the bulk composition of the ore is within the centre of the mss field, then pentlandite or pyrite will not begin to exsolve from the cooling mss until below 400°C. Pyrite and pentlandite do not crystallize together until below 300°C in a copper-free system. However, in the presence of only a few atomic per cent copper, it is likely that pyrite and pentlandite will crystallize in equilibrium with mss and iss at about 500°C (R.E.T. Hill, pers.comm., 1979). Pentlandite continues to exsolve until the nickel content of the residual pyrrhotite (developed from iron-rich mss) is reduced to less than 1 per cent. Final equilibration of the phases does not take place until below 200°C (Fig.10A). The nickel content of pentlandite varies systematically with the nature of the co-existing mineral assemblage (Misra and Fleet, 1973) as indicated in Figure 10A. In pentlandite-pyrrhotite-pyrite assemblages the pentlandite is nickel-poor, whereas in millerite- or heazlewoodite-bearing assemblages it is nickel-rich.

As expected from the bulk compositions of most ores and the crystallization history, pyrrhotite is the most abundant sulphide phase. It is also the last to form after sulphur, nickel and copper have exsolved from mss to crystallize pyrite, pentlandite and chalcopyrite respectively. Hence pyrrhotite forms the matrix to the other opaque minerals. Pyrrhotite occurs as hexagonal (Fe_9S_{10}) and monoclinic (Fe_7S_8) varieties, with the latter predominating in massive ores, and the former being commoner in disseminated ores, where it may represent a metastable phase. Monoclinic pyrrhotite is recognized by its ferrimagnetic nature which produces a lamellar magnetic domain texture when treated with a magnetic colloid suspension. The low temperature exsolution of magnetite or smythite seems to be responsible (Bennett and others 1972, 1972a). Copper may exsolve at low temperature from some pyrrhotites to produce an intergrowth of cubanite ($CuFe_2S_3$).

Ores more nickel-rich than the common compositional field (Fig.10C) are rare, and are best developed in low-grade weakly disseminated sulphide assemblages. Pyrite-millerite ∓ primary violarite/polydymite occurs at Kambalda, Black Swan and Mount Keith. Pentlandite-millerite ∓ pyrite ∓ heazlewoodite is present at Agnew, Kambalda and Nepean. Pyrite – primary violarite-vaesite has been recorded from the Black Swan deposit (Hudson and Groves, 1974). Awaruite is a rare accessory to heazlewoodite-bearing assemblages at Nepean and Mount Keith. Nickeliferous arsenide and sulpharsenide minerals may occur in minor amounts particularly in sulphide mineralization in talc-carbonate rocks and/or associated with sulphidic metasediments (e.g. Lunnon and Jan shoots at Kambalda, Spargoville and Redross).

BEHAVIOUR DURING IGNEOUS PROCESSES

The behaviour of nickel during igneous processes differs considerably according to whether a sulphide phase is present in the system under consideration. In a magmatic system consisting of sulphide liquid and basaltic melt (8.3 per cent MgO) at 1300°C, the partitioning of nickel (Ni^{2+}) into the sulphide liquids is some 250 times greater than that into the silicate liquid (Rajamani and Naldrett, 1978). This demonstrates the chalcophile nature of nickel referred to at the beginning of the chapter. The preference of Ni^{2+} for the sulphide liquid decreases with both increasing temperature and increasing magnesia content (basicity) of the silicate melt. The latter effect is caused by an increase in the number of octahedral sites in the silicate liquid with increasing basicity: nickel has a strong preference for such sites in silicates and liquids.

In a system consisting of basaltic melt and olivine phenocrysts at 1400°C, the partitioning of nickel into the olivine crystals is six times greater than that into the silicate liquid (Leeman and Lindstrom, 1978). This again reflects the preference of nickel for octahedral sites, which in this case are most abundant in the olivine crystal structure, Ni^{2+} having a similar ionic radius (0.69 Å) (0.069nm) to Mg^{2+} (0.66 Å) (0.066nm) and Fe^{2+} (0.74 Å) (0.074nm) which are the chief metallic cations in olivine. The preference of Ni^{2+} for olivine decreases with increasing temperature and increasing magnesia content of both silicate liquid and olivine, which describes the conditions expected in a peridotitic magma system compared with the basaltic system already considered. This change in the degree of preferential partitioning is probably partly the result of an increased proportion of octahedral sites in the magnesium silicate liquid (Cawthorn and McCarthy, 1977).

Pyroxenitic to peridotitic silicate liquids and sulphide liquids therefore have a large capacity for absorbing nickel ions. Except at very low sulphur concentrations these liquids would coexist as immiscible phases because of the low solubility of sulphur (0.1 to 0.4 weight per cent) in basic to ultrabasic silicate melts (Haughton and others, 1974; Shima and Naldrett, 1975). Naldrett and Cabri (1976) suggested that the Archaean mantle was enriched in sulphide liquid droplets at depths (about 200 km or more) corrsponding to the (ultimate) source region of komatiitic magmas, thus accounting for the fundamental relationship between such magmas and most nickel ores. Rapid ascent of a sulphur-saturated magnesium liquid would generate enough heat to allow considerable amounts of surrounding peridotitic mantle to be incorporated and melted (Bickle and others, 1977). This increases the basicity of the silicate liquid and adds nickel derived from melted olivines to this liquid and preferentially to the suspended sulphide liquid droplets, if the magma remains sulphur-saturated.

Clearly then, the behaviour of nickel in basaltic peridotitic magmas evolving at high crustal levels will be very different according to whether the primary magma is sulphur-saturated or not. Without sulphur saturation the fractionation (removal) of olivine will deplete the residual silicate liquid in nickel (and magnesia) to give a curve like that in Figure 7. Differentiation under conditions of sulphur saturation causes the depletion of nickel in the silicate liquid to be far more rapid, and the olivine itself, being in competition with sulphide liquid, is able to trap far less nickel. Using experimentally determined parameters, Duke and Naldrett (1978) have demonstrated these differences with a numerical-model calculation which simulates the low-pressure differentiation of such magmas by the fractionation of olivine and molten sulphide.

The nickel content of segregating sulphide liquids decreases as differentiation of the magmas proceeds because of nickel removal by olivine fractionation. However, the opposite applies in the case of copper because copper (as Cu^+) does not partition into olivine. Thus copper accumulates in the residual silicate liquid to be captured by sulphide liquids when these segregate, copper being strongly chalcophile in nature, like nickel. Therefore the ratio of nickel to copper in sulphide melts should be related to the composition of the host silicate magma at the time of segregation. This is observed to be the case in natural ores as the Ni:Cu ratio decreases with declining magnesia content of the host ultramafic to mafic rock (e.g. Naldrett and Cabri, 1976), and the relationship can be reproduced by calculation using experimentally determined partition coefficients (Rajamani and Naldrett, 1978; Duke and Naldrett, 1978). The relationship is therefore fundamental, and it is used to help in classifying nickel sulphide deposits in this bulletin.

Low-pressure differentiation of silicate magmas containing 12 per cent or less MgO probably involves the fractionation of calcic clinopyroxene in addition to olivine (e.g. Arndt and others, 1977). Under these circumstances the depletion of nickel in the residual liquid is less pronounced, because the partitioning of nickel between clinopyroxene and basaltic liquid is at least five times less than that between olivine and liquid (Duke, 1976). Differentiating tholeiitic basaltic magmas could evolve by the fractionation of orthopyroxene in addition to olivine, but the effect on the partitioning of nickel is likely to be similar to olivine.

In summary, at magmatic temperatures the highest concentrations of nickel are likely to occur in immiscible sulphide liquids which coexist with sulphur-saturated peridotitic silicate liquids derived by high degrees of (probably two-stage) melting of mantle material. The nickel contents of sulphide melts which segregate from less magnesian silicate magmas are likely to be lower, though the copper content will probably be higher. A large proportion of immiscible sulphide droplets in the magma will settle rapidly during emplacement to form a thick accumulation of nickeliferous sulphides.

As the sulphide liquid begins to crystallize mss, it is possible for metal fractionation to take place. For example, separation may take place of a liquid that is copper-rich (point D, Fig.10E) relative to the iron-rich mss (point C) crystallizing in equilibrium with it, down to a temperature of 850°C (Craig and Kullerud, 1969). On the other hand, except at low sulphur fugacities (unlikely in natural systems), the separation of more nickel-rich liquid (point F, Fig.10E) in equilibrium with nickel-rich mss (point E) is only possible above 1000°C. At lower temperatures the crystallizing mss becomes richer in nickel than the co-existing liquid. In between these two extremes of mss composition (say point G), the co-existing liquid contains more nickel and copper. If separated, this liquid would produce ores rich in chalcopyrite and pentlandite.

In the case of sulphide liquids that remain as crystallizing droplets within the solidifying silicate magma such fractionation will not be possible. However, the compositions of disseminated sulphides are more susceptible to modification at submagmatic temperatures (less than 1000°C) by reaction with olivine and pyroxene, because of the lack of a buffering (stabilizing) effect caused by the presence of a large mass of sulphides. Based on the results of experimental studies, Rajamani and Naldrett (1978) predicted that the partition coefficient of nickel between crystallized bulk sulphide (mss) and peridotitic rock, should be higher than that between sulphide liquid and peridotitic liquid. The observations of Binns and Groves (1976) on iron-nickel partitioning between olivine and sulphide at Agnew support this. Therefore mss would be expected to gain some nickel from olivine and orthopyroxene especially. Ewers (1972) has demonstrated experimentally that nickel would be rapidly absorbed by pyrrhotite at elevated temperatures. Because of the very low concentration of copper in these silicates this subsolidus re-equilibration should result in an increase in the Ni:Cu ratio of the disseminated sulphides especially when compared with adjacent massive sulphides. The observed relationship in most Western Australian nickel deposits is the exact opposite, with Ni:Cu ratios in disseminated or matrix sulphides being lower than Ni:Co ratios in associated massive sulphides. However, evaluation is complicated by element redistribution and mineral re-equilibration which occured during the more prolonged conditions of elevated temperature caused by subsequent regional metamorphism.

BEHAVIOUR DURING METAMORPHIC PROCESSES

The geology of most nickel sulphide deposits in the State demonstrates that the deposits have undergone most, if not all, the metamorphic and tectonic events recorded by their host rocks. These deposits are therefore metamorphosed ores (Mookherjee, 1970) being genetically unrelated to the metamorphism, though modified by it. Groves and others (1976) concluded that most of the presently observable feature of volcanic peridotite-associated nickel ores result from the metamorphic modification of pre-existing magmatic sulphides. They also suggested that some massive and matrix ores may have been generated metamorphically from disseminated ores; these massive and matrix ores would then be regarded as metamorphic (Mookherjee, 1970).

Greenschist to amphibolite facies regional metamorphism has effected the majority of nickel sulphide deposits in Western Australia (Binns and others, 1976), therefore sulphide assemblages have undergone at least partial homogenization to mss determined by the phase equilibria in the Fe-Ni-Cu-S-O system as discussed above. McQueen (1979) has confirmed this by heating nickel ores from Redross to 500 and 540°C. In the case of massive sulphides reversion to mss would destroy most of the magmatic layering or inhomogeneities in the ore. The application of tectonic stress to massive sulphides in particular, may cause the physical migration of the lower strength minerals (pyrrhotite, chalcopyrite) into fractures and disrupted zones (Mookherjee, 1976) although preferential diffusion of copper to low-strain areas is an additional possibility (Barrett and others, 1977). In any event, this segregation of copper may be greatly responsible for the commonly higher Ni:Cu ratio of massive sulphides compared with matrix to disseminated sulphides.

The timing of deformation relative to metamorphism may determine the extent to which pyrrhotite migrates in massive sulphides, especially in relation to pentlandite, which, from textural observations, appears to be a higher strength mineral. If deformation is synmetamorphic the ore will exist largely as mss plus pyrite and spinels, thus segregation of pyrrhotite is not possible. If, on the other hand, deformation occurs before or after metamorphism (i.e. at low temperatures) then ductile pyrrhotite (Atkinson, 1975) could segregate from pentlandite thus causing ores to have a wide range of Fe:Ni ratios (Barrett and others, 1977).

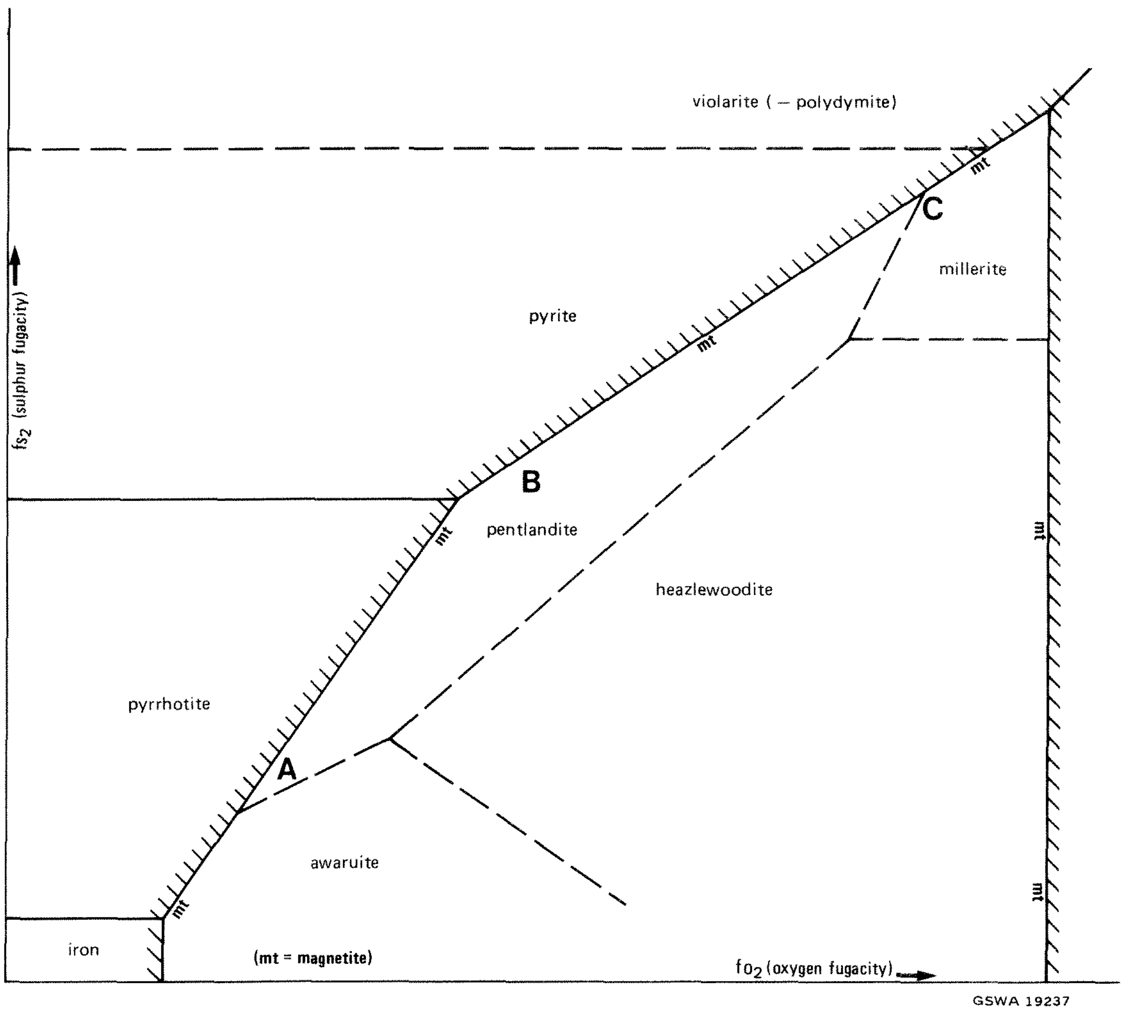


Figure 11. Schematic oxygen versus sulphur fugacity diagram for the Fe-Ni-S-O system showing the stability fields of minerals that co-exist with magnetite. The magnetite field is outlined with hachures. The areas marked A, B, and C, indicate the changes in opaque assemblages from relict olivine-bearing (A) through serpentinized (B) to talc-carbonate (C) ultramafics, proposed by Eckstrand (1975).

Matrix and disseminated sulphides, but especially weakly disseminated sulphides, are susceptible to modification by reaction with the silicate or carbonate minerals which dominate the rock, or by reaction with metamorphic fluids present in the rock. Such reactions may affect massive sulphides marginally (e.g. Marston and Kay, 1980), but the self-buffering capacity (with respect to oxygen and sulphur) of a large mass of sulphide prevents extensive reaction. Furthermore the high S:Ni and Fe:Ni ratios of most massive sulphides require that iron sulphides predominate and prevent the appearance of sulphur-poor nickel-rich minerals (Eckstrand, 1975). In the case of the weakly disseminated sulphides in ultramafic rocks, Eckstrand (1975) has proposed a model in which the opaque nickeliferous mineral assemblage is controlled by metamorphic alteration reactions through iron-related redox mechanisms (Fig.11). The model predicts that incipient serpentinization, which produces hydrogen, should be accompanied by reduced assemblages typified by low-sulphur (and high-nickel) minerals such as awaruite and heazlewoodite. In contrast, talc-carbonate alteration, which produces oxygen, should be accompanied by oxidized assemblages typified by high-sulphur minerals such as millerite. In these alteration reactions 15 moles of olivine produce one mole of hydrogen, and 36 moles of serpentine produce one mole of oxygen, hence redox effects will generally only be important when the rock contains a small amount of sulphide.

Observations on various disseminated sulphide assemblages in intrusive meta-dunites in the Yilgarn Block, rocks which preserve a range of alteration facies from relict dunite through serpentinite to talc-carbonate, tend to confirm Eckstrand's model of increasing oxygen and sulphur fugacity with progressive alteration (Groves and others, 1974; Binns and others, 1977; Groves and Keays, 1979). Dunites which are unaltered or only slightly serpentinized commonly contain pentlandite as the only opaque phase. In more serpentinized dunites heazlewoodite or millerite and magnetite partly replace pentlandite, with some of the nickel required for the formation of heazlewoodite apparently being derived from olivine. Minor amounts of awaruite may be present. The S:Ni and Fe:Ni ratios of the bulk sulphide therefore decrease. Assemblages in highly serpentinized and talc-carbonate rocks are pyrite-millerite magnetite ∓ violarite, pyrite-pentlandite-pyrrhotite, pyrite-vaesite-violarite, and millerite-polydymite-pyrite. Compared with the composition of the original sulphides in the dunite, the bulk compositions of these assemblages require increases in the S:Ni and Fe:Ni ratios. It is important to note that the overall result of nickel, sulphur and iron mobility during progressive alteration processes is for the original amount of nickel present in the sulphide phase to be kept constant, or be depleted by dilution with added iron (from silicates and magnetite) and/or sulphur.

Weakly disseminated opaque assemblages that are more oxidized compared with underlying massive sulphide assemblages characterize some volcanic peridotite-associated deposits (e.g. Kambalda, Nepean). Typically the disseminated sulphides contain more pyrite and magnetite and rarely consist of millerite-pyrite-magnetite ∓ pentlandite. In all cases the hosts are talc-carbonate rocks, so metamorphic oxidation is a possible cause. However, some disseminated milleritic ores at Kambalda (Otter and Gigg shoots) are associated with massive ores of similar composition, and they may partly owe their origin to magmatic fractionation of nickel-rich and/or emplacement under abnormally oxidizing conditions.

Limited diffusional movement of nickel during metamorphism from massive iron-nickel sulphides into barren sulphidic metasediments seems a common phenomenon in volcanic peridotite-associated deposits, where these rock types are adjacent. At Kambalda the metasediments rarely show nickel enrichment for more than a few tens of metres away from the edge of the ore (O.A. Bavinton, pers. comm., 1979). At Windarra the development of some ore-grade material in sulphidic metasediments has been ascribed to the metamorphically-induced migration of nickel from the overlying ultramafic (Seccombe and others, 1978).

During retrograde metamorphism (cooling) metamorphic mss undergoes segregation in a similar manner to that experienced by magmatic mss, although low-temperature re-equilibration is likely to be more complete. Retrogressive serpentinization in areas of high metamorphic grade (e.g. Nepean, Wannaway) may cause oxidation of earlier formed sulphides, as described by Groves and Hudson (1981). Nickeliferous mackinawite ($Fe_{0.95}Ni_{0.08}S$) or bladed magnetite may partly replace pentlandite, and hexagonal pyrrhotite is replaced by monoclinic pyrrhotite or pyrite-magnetitic aggregates. Nickeliferous valleriite (a complex hydrated magnesian iron-copper sulphide) replaces chromites, rims earlier sulphides and occurs as smears along shear zones.

SUPERGENE CONCENTRATION AND DISPERSION

INTRODUCTION

Nickel sulphide deposits in Western Australia have undergone a complex sequence of weathering from at least mid-Tertiary times to the present. Weathering during Tertiary times is generally believed to have been under conditions of heavy rainfall, high water table and a warm, humid, tropical climate.

Deep, lateritic weathering profiles capped with ferruginous or siliceous crusts developed over many different rock types at this time. Later, the climate changed to semi-arid, causing a general lowering of water tables and desiccation of the earlier lateritic profiles. Uplift and tilting also occurred, resulting in the erosion of much of the deeply weathered material. Recently siliceous hard pans have developed in many areas. Ultramafic rocks and their contained sulphide deposits underwent deeper weathering (locally more than 100 m) than most other rocks: primary sulphides do not occur at the surface. Massive sulphides are generally more deeply weathered than disseminated sulphides.

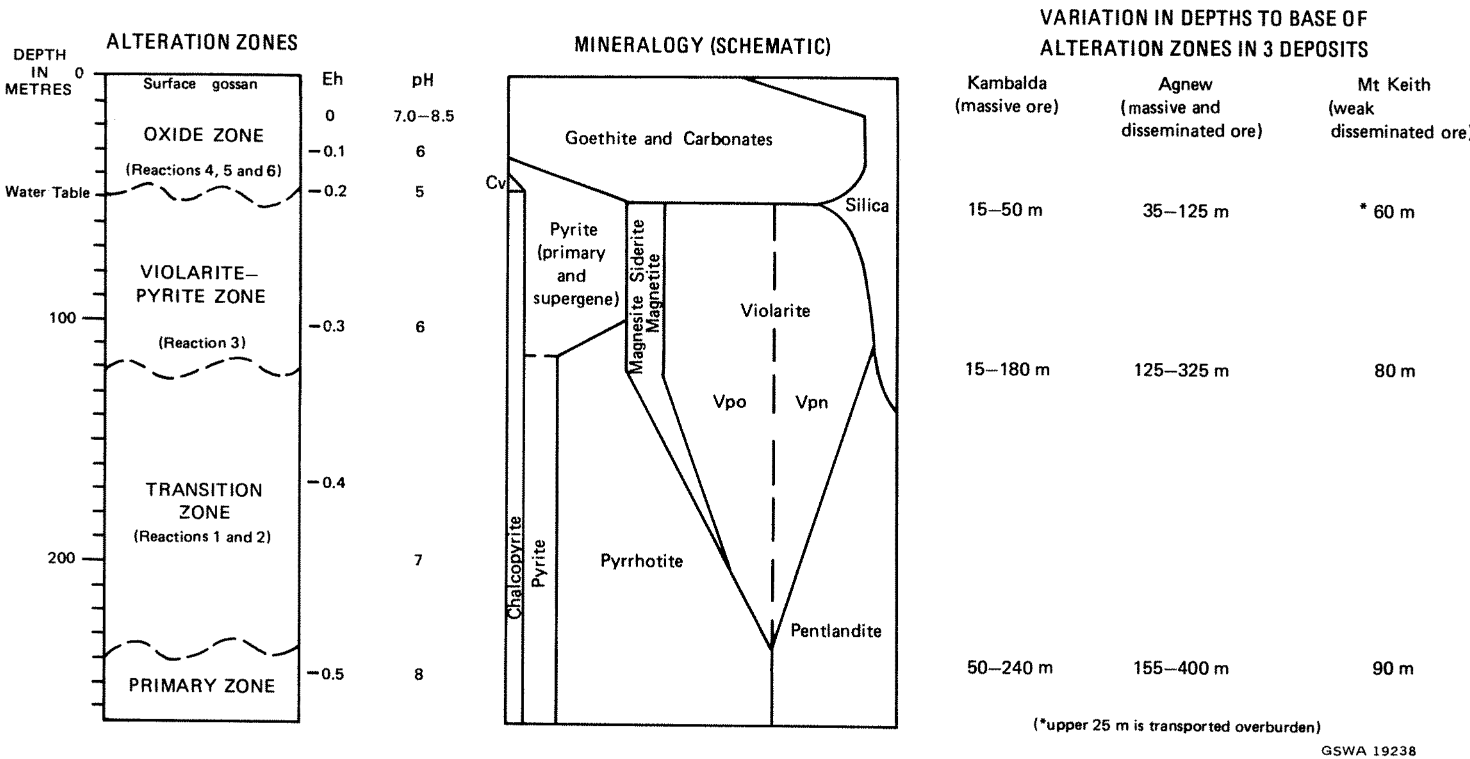


Figure 12. Supergene alteration zones and corresponding mineralogy, with variations in the depths to the base of these zones indicated for three nickel deposits.

The effects of weathering on nickel sulphides in the State were described by Woodall and Travis (1969), for the massive ores of Durkin Shoot, Kambalda. They described three zones of alteration, which Thornber (1972, 1975) refined and explained in terms of an electro-chemical model. Subsequent work has confirmed that this model is generally applicable to massive and disseminated deposits elsewhere, and the following summary is taken from Nickel and others (1974), Nickel and Thornber (1977), and Nickel and others (1977). Reference should be made to Figure 12. However, it must be stressed that complex weathering histories, the geomorphic environment, and permeable structural zones (e.g. faults) all produce variations from this scheme.

There is a sharp change in mineralogy and chemistry between the oxide zone above the present water table and the sulphide-ultramafic assemblages below. Supergene alterations affects sulphides far below the water table: at Agnew specks of the supergene mineral violarite appear in pentlandite in disseminated ore at depths down to 400 m (which represents the base of the transition zone), even though the water table now stands at only 35 m. In the transition and violarite-pyrite zones, pentlandite alters to violarite, and pyrrhotite is converted to pyrite and/or marcasite, and lesser amounts of violarite. These changes are regarded as anodic reactions in an electrochemical model in which the main cathodic reaction is the reduction of oxygen at the water table, thus completing the flow of electrons. These reactions are inhibited in weakly disseminated ores because of a lack of electrical conductivity. Near the water table, nickel enrichment occurs in the violarite-pyrite zone because of partial exchange of nickel for iron in violarite, and of nickel for magnesium and iron in serpentine minerals, talc and carbonates. All sulphides decompose at the water table to produce hydrated iron oxides and various carbonates, but the pseudomorphic replacement textures developed during the anodic reactions are variously preserved, and generally enable the primary mineralogy to be identified in the resulting gossans exposed at the surface.

TRANSITION ZONE

The transformation of pentlandite to violarite (Vpn) proceeds via reaction (1), which marks the beginning of the transition zone:

$Fe_{4.1}Ni_{4.9}S_{8.0}$ →
pentlandite

$Fe_{2.6}Ni_{3.8}S_{8.0} + 1.1Ni^{2+} + 1.5Fe^{2+} + 5.2e^-$ (1)
violarite (Vpn)

The excess nickel ions react with monoclinic pyrrhotite to form less nickeliferous violarite (Vpo), thus:

$0.33Fe_7S_8 + 1.1Ni^{2+}$ →
monoclinic pyrrhotite

$0.33Fe_{3.0}Ni_{3.3}S_{8.0} + 1.32Fe^{2+} + 0.44e^-$ (2)
violarite (Vpo)

In massive ore from the transition zone at Lunnon and Durkin shoots, Vpo contains 29 to 31 weight per cent nickel, whereas Vpn contains 33 to 35 per cent. Cobalt contents also tend to be lower in Vpo compared with Vpn. In hexagonal pyrrhotite-pentlandite assemblages, such as disseminated ore at Agnew, the hexagonal pyrrhotite reacts with the excess nickel to form marginal nickeliferous monoclinic pyrrhotite instead of violarite. The cores of hexagonal pyrrhotite are unstable and change to secondary pyrite before violarite has replaced the pentlandite. When the pyrrhotite cores are completely altered, lamellar violarite replaces the nickeliferous monoclinic pyrrhotite.

The lamellar violarite texture developed around and in pyrrhotite is faithfully preserved during subsequent replacement of pyrrhotite by pyrite, and relicts often remain in the oxide zone where goethite has replaced pyrite. When present in gossans, this lamellar texture is probably the one most diagnostic of underlying nickel sulphide mineralization. Violarite after pentlandite retains the octahedral cleavage of the host, which may still be observed in goethite replacing violarite in the oxide zone.

The excess iron released by reactions (1) and (2) and similar anodic reactions is mainly fixed in siderite (e.g. Kambalda) or secondary magnetite (e.g. Agnew), depending on the amount of carbonate minerals in the gangue of the primary ore, which in turn determines the activity of carbonate species in groundwater.

VIOLARITE-PYRITE ZONE

This zone, which overlies the transition zone, is defined as beginning at the level where the last remnants of primary pyrrhotite and pentlandite disappear. At this level pentlandite has already been completely replaced by violarite (Vpn) so that there is no free nickel available for further formation of lamellar violarite (Vpn). The remaining cores of pyrrhotite are converted to mixtures of secondary nickeliferous pyrite, marcasite and siderite or magnetite via the reaction:

Fe_7S_8 → $4FeS_2 + 3Fe^{2+} + 6e^-$ (3)
pyrrhotite   pyrite

This reaction generally takes place only within 10m or so of the base of the violarite-pyrite zone. Some authors term this interval the "Reactive Zone". The two species of violarite (Vpo and Vpn) developed in the transition zone are retained throughout the violarite-pyrite zone; the relative differences in their nickel contents also remain, though both are enriched in nickel upwards through the zone. Both minerals are porous, due to a volume decrease in reactions (1) and (2), with Vpn being more so. This may allow Vpn to maintain a higher nickel content during reaction with supergene nickeliferous groundwaters. These solutions also give rise to hydrated nickel sulphate minerals (Tables 10 and 11) and increases in the nickel content of siderite-magnesite upwards in the zone. Supergene millerite may occur in patches.

Despite these upward nickel-enrichment trends in supergene minerals, the nickel content of the bulk ore remains little changed. The spectacular supergene enrichments of ore grade seen in many copper sulphide deposits are not a feature of nickel sulphide deposits. The explanation appears to be that nickel enrichment in supergene minerals is balanced by the introduction of secondary quartz and carbonates which contain little or no nickel. The silica probably derives from the breakdown at the water table of ferromagnesian silicate minerals in the ultramafic host rocks.

Chalcopyrite and primary pyrite persist unaltered through the transition and violarite-pyrite zones.

OXIDE ZONE

The oxide zone overlies the violarite-pyrite zone and its base coincides with the water table. Violarite tends to breakdown first, followed by pyrite, releasing many ions into solution according to the anodic reactions (4) and (5) respectively:

$$\underset{\text{violarite}}{FeNi_2S_4} + 16H_2O \rightarrow 2Ni^{2+} + 4SO_4^{2-} + Fe^{2-} + 32H^+ + 30e^- \quad (4)$$

$$\underset{\text{pyrite}}{FeS_2} + 8H_2O \rightarrow 2SO_4^{2+} + Fe^{2+} + 16H^+ + 14e^- \quad (5)$$

Note that this is where the general cathodic reaction (6) takes place:

$$O_2 + 2H_2O + 4e^- \rightarrow 4OH^- \quad (6)$$

This reaction is regarded as the driving force behind the supergene process, with the consumption of free electrons creating a potential gradient which causes anodic conditions in the conductive orebody at depth.

Some of the ions released by reactions (4) and (5) percolate downwards to participate in the creation and enrichment of supergene sulphides. Most of the iron and some of the nickel is fixed in goethite and in nickeliferous carbonates such as nickeloan magnesite, gaspeite, reevesite and takovite. Hematite occurs in preference to goethite in the oxide zone of some massive ores (e.g. Agnew); supergene magnetite is converted to hematite in the oxide zone. Chalcopyrite is replaced by covellite in the oxide zone, with malachite and native copper developing in some localities.

In some deposits the oxide zone contains nickeliferous hydrous silicate minerals such as montmorillonite (Nickel and others, 1977) and talc-like garnierite (Nickel and Bridge, 1975). Weathering profiles over disseminated deposits in serpentinites (e.g. Agnew) may resemble those developed in lateritic nickel deposits which overlie ultramafics essentially devoid of sulphide nickel.

Silica, as quartz or chalcedony and other cryptocrystalline or amorphous forms, is a major component of all oxide zones, particularly in the upper part. This feature may derive from the weathering of the ultramafic rock when the water table was at a higher level (Nickel and Thornber, 1977). Under stable conditions silica would normally be expected to concentrate at the water table where silicate minerals in the ultramafic and other country rocks break down.

The textural and particularly the chemical attributes of nickel gossans are important features requiring careful evaluation in exploration. They are considered in detail in Chapter 8.

Geological setting and diversity of nickel mineralization in Western Australia

GEOLOGICAL SETTING

INTRODUCTION

Nickel deposits in the State are restricted in their distribution, being confined to Precambrian crystalline terrains. The eastern half of the Archaen craton known as the Yilgarn Block accounts for 87 per cent of the identified (demonstrated plus inferred) resources of nickel in Western Australia. Lateritic deposits make up 28.5 per cent of the nickel resources in the eastern Yilgarn Block. The other Archaen craton in Western Australia, the Pilbara Block, though less than one tenth the area of the Yilgarn Block, is very impoverished in nickel mineralization as it contains only 2.6 per cent of the State total of identified resources. Lateritic deposits in the Musgrave block (9.25 per cent) and a sulphide deposit in the Halls Creek Province (1.1 per cent) make up the remainder of the State total. These tectonic provinces consist of Proterozoic crystalline rocks.

Accordingly, the geological setting of rocks favourable for nickel mineralization can be broadly divided into:

(a) Archaean cratons consisting of granitoid-gneiss-supracrustal ('greenstone') terrains, typified by a wide range of metamorphic grade and tectonic style; represented by the Yilgarn and Pilbara Blocks.

(b) Proterozoic metamorphic belts characterized by polyphase metamorphism, deformation and igneous activity; represented by the Musgrave Block, Halls Creek Province, Albany-Fraser Province, Gascoyne Province, and the Rudall Metamorphic Complex.

YILGARN BLOCK

GENERAL

The Archaean rocks of the Yilgarn Block form an area of some 650 000 km^2. The northwestern and southern margins of the block are structural and metamorphic boundaries with the Gascoyne and Albany-Fraser provinces respectively. The meridional Darling Fault forms the western boundary, with the graben-like, Phanerozoic Perth Basin lying to the west. The Nabberu and Officer sedimentary basins unconformably overlie the block to the north and east.

The Yilgarn Block was formerly divided into three provinces (the Eastern Goldfields, Murchison and Southwestern Provinces) primarily on the basis of structural trends, metamorphic grade and major lithological associations (Williams, 1974; Gee, 1975). However, recent mapping has cast doubt on the validity of this style of division and the scheme adopted by Gee (1979) is employed here. The high grade gneissic rocks which characterized the Southwestern Province are now known to extend along the northwestern margin of the block, and their southeastern extent has been redefined. This comprises the 'West Yilgarn gneiss domain.'

The West Yilgarn gneiss domain is characterized by an abundance of felsic gneissic rocks, especially paragneisses, and by having supracrustal rock associations dominated by psammitic to pelitic metasedimentary lithotypes. The grade of regional metamorphism is in the amphibolite to granulite facies over most of the domain, and some gneissic rocks have yielded the oldest Rb-Sr isotopic ages (2 900 to 3 100 m.y.) so far obtained from the Yilgarn Block. The gneisses are intruded by voluminous granitoid rocks which yield Rb-Sr isotopic ages of 2 600 to 2 700 m.y. Mafic and ultramafic rocks are rare and include garnetiferous peridotite, serpentinized peridotite, metapyroxenite and gabbro in small intrusions, hornblende-andesine amphibolite, and pyroxene and/or hornblende granulites. Identifiable ultramafic volcanic or dunitic rocks are lacking, and there is no evidnce at present to suggest that rocks of komatiitic affinity occur. Nickel deposits are absent, with the exception of small lateritic deposits at Byro, and minor occurrences of nickel sulphides in a metamorphosed ultramafic intrusion at Yornup. This gneiss domain is not considered further in this chapter.

The remainder of the Yilgarn Block consists of (i) linear to arcuate belts of variable metamorphosed (prehnite-pumpellyite to amphibolite facies), folded and faulted supracrustal volcanic rocks cogenetic intrusives and sedimentary rocks; with (ii) intervening, more expansive areas of granitoid and lesser gneissic rocks. This is the more familiar, so-called 'granite-greenstone' terrain. with rare exceptions the contacts between supracrustal and granitoid-gneissic rocks are tectonic or intrusive, with the granitoid rocks being younger. As in the West Yilgarn gneiss domain, the late- or post-tectonic granitoids are the most voluminous element in the terrain and Rb-Sr isotopic ages in the range 2 600 to 2 700 m.y. are typical of them. Deformed granitoid, migmatite and banded gneiss are less common.

The supracrustal rocks comprise (a) mafic to ultramafic volcanic sequences of tholeiitic and komatiitic affinity and cogenetic intrusives; (b) felsic volcanic complexes, dominantly of sodic-rhyolite to dacite composition; (c) rare calc-alkaline volcanic centres; (d) clastic sedimentary sequences of volcanogenic and subordinate granitoid provenance; and (e) chert, banded iron-formation and sulphidic slate interspersed in the layered sequences. Layered and differentiated intrusions of peridotite-pyroxenite-gabbronorite-gabbro-anorthosite are emplaced in the layered sequences, but, like these sequences, are themselves intruded by late-tectonic granitoids. Of more restricted occurrence are lenticular, generally conformable intrusions of olivine-rich ultramafic typified by medium- to coarse-grained olivinite to dunite.

NORSEMAN-WILUNA BELT

Definition

By 1971 discoveries of nickel deposits in the eastern Yilgarn Block had resulted in a mineralized zone extending from Norseman to Wiluna being called informally the "nickel belt". McCall (1972) formally termed this belt the "Wiluna-Norseman nickel province" and described its characteristics. Because of a lack of exploration success elsewhere in the Yilgarn Block, he regarded the province as enclosing the known nickel sulphide deposits. The only deposits of importance discovered since are in the Forrestania region, which lies outside McCall's province. Williams (1974), though not referring to McCall (1972), described a similar but smaller area termed the "Norseman-Wiluna region" and gave it the status of a lithostructural subdivision of the Eastern Goldfields Province, which he called the "Kalgoorlie Subprovince". An abundance of nickel-bearing ultramafic rocks, gold deposits, younger volcanic and sedimentary rocks, and chert (almost to the exclusion of magnetic banded iron-formation) were the main features used by Williams (1974) to characterize the region. He interpreted the region as an incipient graben developed in earlier-formed Archaean crust. Williams's Norseman-Wiluna region excludes the nickel and gold deposits of the Laverton area mainly because of the presence of banded iron-formations there.

Gee (1975) described a metallogenically important belt, some 200 km wide and 800 km long, as the "Norseman-Wiluna belt", an area larger than that of Williams (1974) but one nearly coincident with the Wiluna-Norseman nickel province of McCall (1972). The Norseman-Wiluna belt concept was retained by Gee and others (1976) and Gee (1979), who described the regional geology and mineralization, and tectonic aspects of the belt respectively. Their definition of the belt is used in this bulletin (Plates 1 and 2). A continuous corridor of post-tectonic porphyritic adamellite separates the belt from the remainder of the Yilgarn Block to the west. Banded iron-formations are a conspicuous component of Archaean supracrustal assemblages immediately to the west of the Norseman-Wiluna belt. A corridor of more diverse granitoid rocks, migmatite and gneiss separates the belt from the remainder of the block to the east. Gee (1979) makes a structural distinction between these flanking "external" granitoid terrains and "internal" granitoids which are ovate, composite, partly coalescing domal plutons that intrude continuous Archaean supracrustal terrains within the belt. The northern margin of the belt is defined by an unconformity with Proterozoic rocks of the Nabberu Basin. The Albany-Fraser Province forms the southern margin.

Age

Granitoid and lesser gneissic rocks, which together make up about 60 per cent of the belt, range in composition from granite to tonalite, with the overwhelming majority being near the granodiorite-adamellite boundary (Davy, 1978; Archibald and others, 1978). Fractionated leuco-adamellite and syenite are rare. The granitoids form crudely concordant pre-tectonic or syntectonic bodies (Platt and others, 1978; Archibald and others, 1978), and more voluminous late- to post-tectonic batholiths. These granitoids yield Rb-Sr isotopic ages mainly in the span 2 600 to 2 700 m.y. Banded gneisses, some associated with quartzite, iron-formation, calc-silicate rocks, amphibolite and ultramafic schist, are intruded by the granitoids and from several lines of evidence they seem to be older than both granitoids and supracrustals (Gee, 1979). Lead isotope and samarium-neodymium studies both point to the existence of continental crust at least 3 000 m.y. old (Oversby, 1975; McCulloch and Wasserburg, 1978). Evidence for the depositional age of the supracrustal sequences is scant but a late Archaean age seems probable. In the northern part of the belt volcanic rocks formed more than 2 700 m.y. ago, and coarse clastic rocks were laid down between about 2 650 and 2 600 m.y. ago after the emplacement of a sodic granitoid pluton (Cooper and others, 1978; Marston, 1978). Various isotopic ages obtained from supracrustal and granitoid rocks indicate that metamorphic events in the belt span the range from 2 700 to 2 550 m.y.

Rock distribution and stratigraphy

The most obvious and important regional feature of the belt is a structure striking north-northwest, defined by the elongation of individual supracrustal belts, the axial traces of major folds, and the trend of strike faults and tectonic lineaments. The gross distribution of certain supracrustal rock types also appears to be controlled by this trend (Williams, 1974). Ultramafic rocks in general are most abundant in the Menzies-Norseman and Leonora-Wiluna areas (Plate 2). In particular the distribution of mineralized olivine-rich ultramafic intrusions is partly related to tectonic lineaments defined by steeply inclined or vertical ductile shear zones, across which there is commonly little or no correspondence in structure and stratigraphy (e.g. Gower, 1976). Some such lineaments are more than 300 km long, but they do not appear to transect internal granitoids (Gee, 1979), though granitoids either side may have distinct geochemical features (Davy, 1976).

The strike faults and lineaments break up the belt into tectonic slices. This makes regional and even local stratigraphic correlation difficult and adds to the problems caused by lateral facies changes and the large gaps in outcrop (e.g. salt lakes, duricrust plateaux). A good example is provided by the several interpretations of stratigraphy

TABLE 13. LOCAL STRATIGRAPHIC SUCCESSIONS IN THE NORSEMAN—WILUNA BELT

Kambalda (Gresham, 1978)		Agnew (Lawlers) (Naldrett and Turner, 1977; Platt and others, 1978)	Norseman (Doepel, 1973)
Merougil Beds >4000 m >500 m	Conglomerate, sandstone siltstone Felsic and intermediate volcanics	Felsic volcanogenic sediments, >300 m Mt White pillow basalts (Fe-poor); about 800 m	Mount Kirk Formation: felsic volcanics, volcanogenic sediments, chert, black shale, basic volcanics (minor) >3000 m
Hangingwall Basalt (upper) >500 m	Massive komatiitic and tholeiitic basalt	Volcanogenic sediments, acid volcanics, cherts, shales, polymictic conglomerate at base; about 3000 m	Woolyeenyer Formation: pillow basalt with minor graphitic slate, minor komatiitic basalt up to 8000 m
Sediment-intrusive complex 40 m	Sulphidic cherty sediments, intermediate intrusives	Basalt (Fe-rich)	Noganyer Formation: banded iron-formation, conglomerate, sandstone, felsic volcanics; >75 m
Hangingwall Basalt (lower) 60-100 m	Pillowed komatiitic and tholeiitic basalt, with varioles	Lawlers ultramafic: komatiitic basalt to peridotite (about 3000 m)	
Kambalda Ultramafic Formation 150-800 m	Flows of komatiitic picrite, periodotite and olivine peridotite with interflow sulphidic sediments, nickel ore at or near base	Basalt (Fe-poor)	
		Interlayered gabbro, differentiated gabbro-pyroxenite, basalt and pelitic sediment	Penneshaw Formation: pillow basalt, minor siltstone, sandstone; >300 m
Footwall Basalt >1500 m	Tholetiitic basalt, some pillowed		
	Intrusive sodic granite	Intrusive sodic granitoids	Intrusive granitoids

made for the Agnew-Kathleen Valley area (Durney, 1972; Marston and Travis, 1976; Bunting and Williams, 1976; Naldrett and Turner, 1977; Platt and others, 1978). However, in several places in the belt stratigraphic studies (Gemuts and Theron, 1975; McDonald, 1976; Goss, 1977) suggest that only ultramafic rocks towards the base of the succession are hosts to important nickel mineralization. Examples of local successions, which are generally in the range of 7 to 15 km in thickness, are given in Table 13.

CENTRAL AND NORTHWESTERN REGION

This region is similar in general geology and age to the Norseman-Wiluna belt but there are important differences in structure, abundance of ultramafic rocks, and the composition of some supracrustal sequences. The linear structural elements characteristic of the Norseman-Wiluna belt are mainly lacking; arcuate belts of supracrustal rocks wrap around ellipsoidal granitoid bodies in a style resembling the Pilbara Block. However, a linear structure is evident in the southern segment of the region in the Southern Cross — Forrestania — Lake Johnston area (Plate 1). Furthermore this segment is the only one in which olivine-rich ultramafics are developed, with some of these rocks containing important nickel deposits. A higher grade of metamorphism also characterizes this segment in contrast to the majority of the remainder where very low to medium metamorphic grades prevail.

The presence of banded iron-formation and chert either forming thick multiple units accompanied by felsic clastic and volcaniclastic sedimentary rocks, or occurring as generally thinner units throughout mafic to ultramafic volcanic sequences, is typical of the whole region. Abundant differentiated mafic to ultramafic sills and layered intrusions are a feature of the north-central part of the region in the Meekatharra-Sandstone-Ninghan-Yalgoo area. Some of these bodies contain titanium-vanadium-bearing magnetite deposits, but nickel deposits seem to be lacking, apart from one occurrence near Cue.

Excepting the southern segment, the structure and abundance of iron formations and differentiated intrusions in the remainder of the region may indicate greater crustal stability during the development of the supracrustal sequences than is apparent for the Norseman-Wiluna belt. Basal quartzitic rocks underlie the volcanic supracrustals in much of the central Yilgarn (R.D. Gee pers. comm., 1979), and this also suggests an early continental crust and more stable conditions. Hence, perhaps, the lack of olivine-rich ultramafics and associated nickel deposits in the region may be explained.

PILBARA BLOCK

GENERAL

The geology of the Pilbara Block is described in detail by Hickman (in press) and the following summary is largely taken from this source. The block occupies an area of some 60 000 km^2 and is bounded by the Indian Ocean to the northwest (Fig. 13). The remaining margins of the block are defined by unconformities with Lower Proterozoic rocks of the Hamersley Basin to the west, south and east, and Phanerozoic rocks of the Canning Basin to the north and northeast. A series of small domal inliers of Archaean rocks, the largest of which is the Sylvania Dome (150 by 50 km in outcrop), are present within and at the margins of the Hamersley Basin. Therefore, Archaean rocks similar to those exposed in the Pilbara Block probably underlie the whole of the Hamersley Basin thereby outlining the Pilbara Craton (Gee, 1979).

In terms of general geology the Pilbara Block resembles that portion of the Yilgarn Block to the east of the West Yilgarn gneiss domain, especially the northwestern part (Murchison region). Granitoid and lesser gneissic rocks which together make up about 60 per cent of the block, range in composition from alkali feldspar granite to tonalite and form ovoid domal batholiths composed of numerous separate units. These units fall into three main categories: (i) a migmatitic, gneissic and foliated granitoid complex metamorphosed at about 3 000 m.y.; (ii) porphyritic adamellite and granodiorite which intrude category (i) rocks; and (iii) post-tectonic granite to adamellite plutons and stocks with Rb-Sr isotopic ages of 2 600 to 2 700 m.y. The

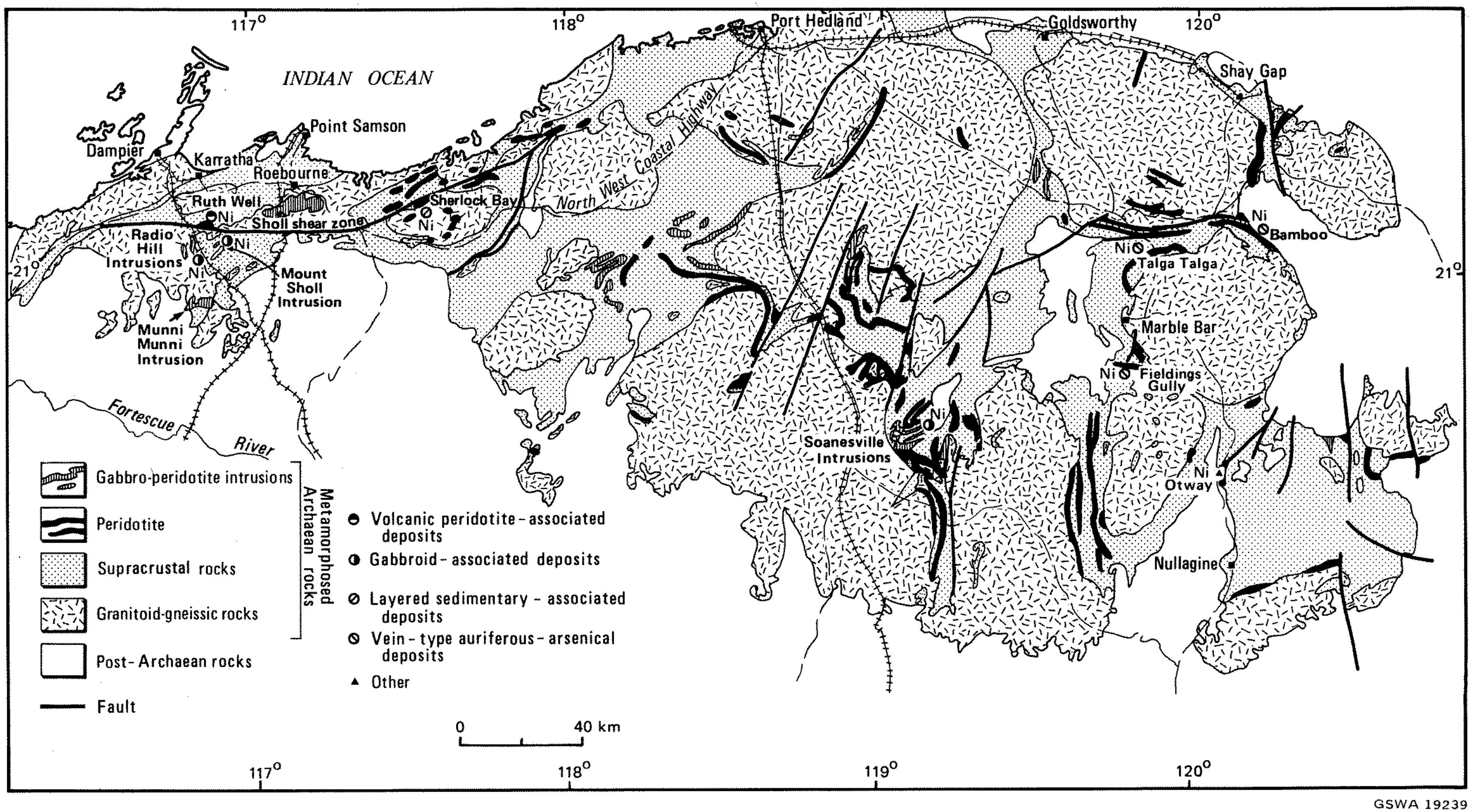


Figure 13. **Generalized geological map of the Pilbara Block showing the distribution of intrusive ultramafic rocks, nickel deposits, and major faults.**

TABLE 14. SUMMARY STRATIGRAPHY OF THE PILBARA SUPERGROUP

Group	Subgroup	Formation and thickness in km	Lithology (pre-metamorphism)	Nickel mineralization and remarks
		Negri Volcanics (0.2)	variolitic basalt	
		unconformity		
		Louden Volcanics (1.0)	Komatiitic basalt to peridotite, some andesite	
		unconformity		
Whim Creek Group		Rushall Slate (0.2) Mons Cupri Volcanics (0.5) Warambie Basalt (0.2)	Felsic volcanics amygdaloidal basalt	Low grade nickel-copper deposits at Sherlock Bay are probably in a sequence equivalent to this group (isotopic age 2 550 to 2 750 m.y.)
		unconformity		
Gorge Creek		Mosquito Creek Fm (5.0) Lalla Rookh Sandstone (3.0) Honeyeater Basalt (1.0)	Clastic sedimentary, pillow basalt, and minor komatiitic basalt	Turbiditic sediments shallow water sediments not widespread throughout the Pilbara Block
Group	Soanesville Subgroup	Cleaverville Formation (1.0) Charteris Basalt (1.0) Corboy Formation (1.5)	Banded iron-formation pillow basalt and minor komatiitic basalt Clastic sedimentary	Most basalt contains 12% MgO in type area; not a widespread formation
		local unconformity		**
Warrawoona Group		Wyman Formation (1.0)	Felsic volcanics	Highly fractionated compared with Duffer Fm
		local unconformity		
	Salgash Subgroup	Euro Basalt (2.0) Panorama Formation (1.0) Apex Basalt (2.0)	Pillow basalt and komatiitic basalt to peridotite Felsic volcanics, chert Pillow basalt and komatiitic basalt to picrite	Less magnesian than the Apex Basalt in general Important stratigraphic marker Isotopic age > 3 300 m.y.
		local unconformity ?		
		Towers Formation (0.5)	Chert with minor basalt and komatiitic basalt	Important stratigraphic marker
		Duffer Formation (5.0)	Felsic volcanics	Isotopic age 3 450 to 3 500 m.y.
		local unconformity		
	Talga Talga Subgroup	Mount Ada Basalt (2.0)	Basalt, rare komatiitic basalt	
		McPhee Formation (0.1)	Carbonate-chlorite-quartz schist (probably metasomatized komatiitic picrite) and chert	Present in the subgroup are small, uneconomic nickel sulphide deposits at Ruth Well, West Pilbara
		North Star Basalt (2.0)	Basalt, rare picrite and peridotite	

Notes:

* low grade copper-nickel deposits occur in the Mount Sholl intrusion which is emplaced at this stratigraphic level (according to Hickman) (in press).

** nickel arsenide mineralization at Bamboo is contained in a carbonated ultramafic intruded at this stratigraphic level (according to Hickman) (in press).

domal batholiths have tectonic or intrusive contacts with metamorphosed supracrustal volcanosedimentary rocks some of which have yielded U-Pb and Pb-Pb isotopic ages in the range 3 340 to 3 500 m.y. The supracrustal rocks (Pilbara Supergroup) occur in irregular, faulted synclinorial structures which separate the domal batholiths. The depositional age range of the Pilbara Supergroup is probably some 1 000 m.y., as available isotopic evidence suggests that the Whim Creek Group, the youngest part of the supergroup, is between 2 550 and 2 750 m.y. old. However the Warrawoona Group was possibly laid down in 200 m.y. or less (A.H. Hickman, pers. comm., 1979).

PILBARA SUPERGROUP

The Pilbara Supergroup crops out over an area of 24 000 km^2 and ranges in true thickness from 15 to 30 km. The stratigraphy of the supergroup, as deduced by Hickman (in press), is summarized in Table 14. The Warrawoona Group, a mainly volcanic assemblage of mafic, felsic and ultramafic rocks with minor chert, is overlain by the Gorge Creek Group, a mainly sedimentary sequence of sandstone, conglomerate, greywacke, shale and banded iron-formation with minor basalt and gabbro. In the west Pilbara an upper calc-alkaline volcanic unit of restricted distribution, the Whim Creek Group, unconformably overlies the Gorge Creek and Warrawoona Groups, and is itself overlain by two further mafic volcanic formations.

Komatiitic basalts and ultramafic volcanics are developed throughout the succession, but are concentrated in the Apex Basalt, Euro Basalt and Louden Volcanics (Table 14). Overall, the most magnesian formation appears to be the Apex Basalt (see Table 7), though olivine-rich ultramafic volcanics seem to be rare or lacking in this formation and the rest of the supergroup. The only nickel deposits known of the volcanic peridotite-associated type occur at Ruth Well, close to the largest linear dislocation recognized in the Pilbara — the Sholl shear zone. This zone also passes close to the Sherlock Bay nickel-copper deposit which occurs in a volcanic setting but appears to be of exhalative origin.

Intrusive ultramafic rocks occur as (i) thin, laterally extensive, essentially single-rock-type sills or dykes; and (ii) in thick, layered mafic to ultramafic intrusions (Fig. 13) Category (i) rocks are mainly partly altered peridotite and pyroxenite, serpentinized peridotite to dunite, talc-carbonate, and talc-tremolite-chlorite-carbonate assemblages. Many of the discordant intrusions occupy major fault zones. Examples include the peridotite-serpentinite unit which extends 70 km from Bamboo Creek to Pear Creek, and the peridotite along the southern contact of the Mosquito Creek Synclinorium. Category (ii) rocks form part of a spectrum of compositions ranging from dunite to anorthosite derived from parent magmas of both tholeiitic and komatiitic affinities. In general there appear to be no common structural or stratigraphic controls governing the distribution of either category of intrusive rocks, with the exception of the faults already mentioned. Layered intrusions are commonest in the west Pilbara.

Nickel deposits in category (1) rocks are only known from Bamboo Creek where low-grade nickel arsenides are disseminated in a faulted zone in a carbonated ultramafic. Some layered intrusions or differentiated sills contain small deposits and occurrences of iron-nickel-copper sulphides in basal or marginal ultramafic zones. The known mineralized intrusive complexes are at Mount Sholl, Radio Hill, Munni Munni and Soanesville. Small deposits, as distinct from occurrences, are restricted to the Mount Sholl intrusion which is situated adjacent to the Sholl shear zone.

An important feature of the bulk of the Pilbara Supergroup is its essentially continuous stratigraphy over large distances. As pointed out by Gee (1979), this requires overall basement stability during an extended period of widespread volcanism (represented by the Warrawoona Group) that was apparently unrelated to the style of linear tectonics that characterizes the Norseman-Wiluna belt. These differences in crustal evolution appear to have important metallogenic consequences for the Pilbara Block. The absence of linear tectonic control is probably a reason for the lack of olivine-rich ultramafic volcanics and dunite to olivinite intrusives, and therefore a lack of important nickel mineralization. Importantly, the known nickel deposits in the Pilbara are spatially related to major fault structures. If a sulphide-rich zone of the mantle was evolving during the Archaean, the time at which ultramafic liquids were generated from the mantle could have been critical. Available evidence suggests that most ultramafic rocks in the Pilbara Block are likely to be considerably older than counterparts in the Yilgarn Block.

MUSGRAVE BLOCK

The western third of the Musgrave Block extends into Western Australia, and this portion has been described by Daniels (1974). For the pruposes of this bulletin the Middle Proterozoic sedimentary and volcanic rocks of the Bentley Supergroup are excluded from the Musgrave Block. Felsic granulites, migmatites, gneisses and granitoids make up the bulk of the block. Some granulite has yielded Rb-Sr isotopic ages of about 1 400 m.y. Nickel mineralization has not been reported from these rocks.

The high-grade metamorphic rocks and granitoids of the block are intruded by the layered gabbroidal rocks of the Giles Complex, a name given to numerous separate igneous masses of several ages which occur in central Australia in an area perhaps up to 34 000 km^2 in extent. Four main masses are recognized by Daniels (1974) in the State:

(1) Jameson Range Gabbro is up to 5 500 m thick and consists of gabbro, ilherzolite, troctolite, and anorthosite.
(2) Blackstone Range Gabbro is about 3 350 m thick and consists of troctolite, norite and gabbro.
(3) Michael Hills Gabbro is 6 400 m thick and includes gabbro, anorthosite and pyroxenite.
(4) Hinckley Range Gabbro is possibly 2 700 m thick and consists mainly of norite and gabbro.

Marginal contamination of gabbro by granulite, granophyric dykes and cappings, and igneous layering are features common to all the masses.

The Hinckley Range Gabbro occupies a north-northwest-striking syncline, along the northern side of which, near Wingelinna, is a lateritic and ochreous nickel deposit. The deposit appears to be confined to sheared and altered pyroxenite and dunite, some of which may have been intruded into earlier shears in gabbro (Sprigg and Rochow, 1975).

Daniels (1974, p.234) mentioned an occurrence of a rare mineral, possibly pentlandite, in drillcore of gabbro from the Michael Hills Gabbro. No other nickel occurrences are known from the Giles Complex.

HALLS CREEK PROVINCE

The Lower proterozoic igneous and metamorphic rocks of this province have been arbitrarily divided into the Halls Creek mobile zone (east of 126°E) and the King Leopold mobile zone in the west (Thom, 1975). Older supracrustal rocks, termed the Halls Creek Group and Tickalara Metamorphics, are most extensive in the Halls Creek mobile zone where radiometric ages of 2 050 m.y. to 2 100 m.y. are indicated for these rocks (Page, 1976). A suite of variably metamorphosed mafic to ultramafic igneous complexes, diferentiated sills and layered intrusions was emplaced into the older supracrustal rocks before or during regional metamorphism. Again, these igneous rocks are best developed in the Halls Creek mobile zone. An older granitoid suite (e.g. Mable Downs Granodiorite) intrudes the above rocks but is itself unconformably overlain by younger supracrustal rocks (e.g. Whitewater Volcanics) which are probably about 1 950 m.y. old (Page, 1976). Younger granitoid batholiths (e.g. Bow River Granite) intrude the Whitewater Volcanics and older rocks.

Ultramafic volcanic rocks have not been found in any of the supracrustal sequences, and interest for present purposes centres on the mafic to ultramafic intrusive suite. The suite has been subdivided as follows (Gemuts, 1971; Thom, 1975):

(1) Woodward Dolerite — undifferentiated dykes and sills of altered dolerite, gabbro and pyroxenite intruded into the Halls Creek Group throughout the province;
(2) Wombarella Quartz Gabbro — quartz gabbro and norite, tonalite, restricted to a small area in King Leopold mobile zone;

(3) McIntosh Gabbro — differentiated sills and igneous complexes of altered gabbro, norite, troctolite and minor peridotite intruded into the Tickalara Metamorphics (Halls Creek mobile zone only); and

(4) Alice Downs ultrabasics — the differentiated basal fraction of the McIntosh Gabbro comprising altered pyroxenite, peridotite, anorthosite and chlorite-tremolite schist.

Deposits and occurrences of iron-nickel-copper sulphides are known from norite and gabbro assigned to the McIntosh Gabbro.

ALBANY-FRASER PROVINCE

This province covers an area of some 50 000 km^2 to the southeast of the Yilgarn Block, being bounded to the south by the Southern Ocean and to the east by the Eucla Basin. The western boundary of the province with the Yilgarn Block is commonly a transitional tectonothermal front termed the Fraser Front by Gee (1979). Felsic orthogneiss, paragneiss, gneissic granite, granitoids, migmatite, and mafic granulite (Fraser Complex) are the main rock types (Doepel, 1975). In the northeastern part of the province high-grade regional metamorphism, acid and basic igneous activity, and tectonism occupied the period 1 300 to 1 900 m.y. ago (Bunting and others, 1976). Late- to post-tectonic batholiths in the Albany area were emplaced in the period 1 000 to 1 200 m.y. ago. Clearly supracrustal rocks which are involved in the province are the "Stirling-Barren Series" in the west which transgress the Fraser Front, and the Mount Ragged Beds in the east occurring wholly within the province. These rocks consist of quartzite, phyllite, quartz-mica schist, quartz-pebble conglomerate, quartz-feldspar porphyry and rare carbonate rocks. Reworked Archaean rocks have been recognized within the province, especially near the Fraser Front.

Nickel occurrences appear to be restricted to small, irregular instrusions of deformed and metamorphosed norite-pyroxenite-peridotite emplaced in the southern end of the mafic granulite of the Fraser Complex (Tyrwhitt and Orridge, 1975). The Fraser Complex can be interpreted as a floored structure of supracrustal origin originally largely made up of mafic volcanics and intrusives (Gee, 1979).

GASCOYNE PROVINCE

The Proterozoic metamorphic and igneous rocks of the Gascoyne Province occupy an area of 50 000 km^2 in the northwestern part of the State. The southern boundary with the Yilgarn Block is gradational but can be defined by a series of east-northeast-trending shear zones, arranged en echelon in an east-west direction, which mark the overprinting of Archaean rocks by Proterozoic fabrics (Elias and Williams, 1977). The eastern boundary on the Robinson Range Sheet is a tectonic or unconformable contact with cover rocks of the Padbury Group (Elias and Williams, 1977). Elsewhere the eastern and northern boundary corresponds with the western unconformable margin of the younger Bangemall Basin, except to the extreme north where a gradational boundary with the Ashburton Fold Belt (Gee, 1979) is present. Permian sedimentary rocks of the Carnarvon Basin bound the province to the west.

In the northern part of the province greywacke, shale, arkose, quartzite, conglomerate, basalt and dolomite have been affected by greenschist to amphibolite facies regional metamorphism, and intruded by syn- to post-tectonic granitoids 1 600 to 1 900 m.y. old. In the southern part of the province, in addition to the granitoids and the metamorphosed supracrustal rocks, there are large areas of migmatite and gneiss which contain igneous and sedimentary rocks metamorphosed to the high amphibolite or granulite facies. These gneissic areas have been interpreted as reworked Archaean basement by Elias and Williams (1977). Small elongate belts of clastic rocks (Mount James Beds) unconformably overlie the reworked basement, the metamorphosed supracrustals and the granitoids, and are found throughout the province.

Ultramafic rocks are very rare in the province and are only present in the southern part. Reworked Archaean layered supracrustal rocks in the Trillbar Belt and near Bedaburra Creek (central Robinson Range Sheet) include tremolite-chlorite schist and serpentinized peridotite (Elias and Williams, 1977). Metamorphosed Proterozoic supracrustals and reworked basement in and adjacent to the Errabiddy shear zone on the eastern-central part of the Glenburgh Sheet are intruded by small plug-like bodies of serpentinized peridotite (Williams and others, 1980). Significant nickel mineralization has not been recorded from the Gascoyne Province.

RUDALL METAMORPHIC COMPLEX

The Rudall Metamorphic Complex (Chin and others, 1979) crops out in the central-eastern part of the Paterson Province (Williams and others, 1976), and forms about 20 per cent of the exposed area of the province.

Two distinct, interfoliated metamorphic sequences with different structural histories make up the Rudall Metamorphic Complex. The older sequence consists of metasedimentary, mafic and ultramafic gneiss and banded quartzite which originally formed a layered succession. This succession was intruded by granitoid rocks and both were then strongly deformed (D_1 deformation) and metamorphosed to produce the gneissic terrain. The younger sequence is mainly quartzite and quartz-mica schist which formed from sedimentary rocks laid down on the older gneiss. The subsequent deformation (D_2) and metamorphic event are propgrade in the younger sequence but are responsible for the retrogression of the older sequence. Small bodies of post-tectonic adamellite were intruded into the complex before the cover sequence rocks of the Yeneena Group were deposited.

Reliable radiometric age dating of the Rudall Metamorphic Complex has not yet been carried out. The older sequence is derived from rock types and associations that closely resemble Archaean terrains (Chin and others, 1979). Ultramafic rocks (metamorphosed peridotite and pyroxenite) occur as isolated small bodies intruded by granitoid and gneissic rocks. A later generation of small (up to 1 km in diameter) intrusive ultramafic bodies were emplaced into the complex before or during the D_2 deformation. Serpentine $\mp$ chlorite $\mp$ tremolite (peridotitic) rocks are the most common components of these bodies, and some exhibit coarse-grained relict cumulate textures. Smaller bodies may include coarse-grained amphibole ∓ chlorite (pyroxenitic) rock. Significant nickel mineralization has not been recorded from the Rudall Metamorphic Complex.

TYPES OF DEPOSITS

CLASSIFICATION

Nickel deposits in Western Australia are classified as follows. Firstly a division is made between (a) nickeliferous sulphide deposits and (b) nickeliferous laterite deposits. The lateritic deposits are not subdivided. The nickel sulphide deposits are subdivided using the following criteria:

- (i) the basicity of the host rock (MgO content);
- (ii) the intrusive versus volcanic origins of the host rock and its associated sequence;
- (iii) the presence of petrological trends ascribable to gravity differentiation of the host;
- (iv) the range of bulk Ni: Cu ratios of the sulphide assemblages;
- (v) the presence of interbedded sulphides and host rock; and
- (vi) the presence of vein-type mineralization.

More than one criterion may be needed to classify a deposit, but the following five types of sulphide deposits are recognized:

1. *Intrusive dunite-associated deposits* (e.g. Mount Keith). Ni:Cu typically greater than 19, MgO generally greater than 45 per cent.
2. *Volcanic peridotite-associated deposits* (e.g. Kambalda. Ni:Cu typically in the range 7 to 19, MgO generally in the range 38 to 45 per cent.
3. *Gabbroid-associated deposits* (e.g. Sally Malay). Ni:Cu typically less than 7, host rocks partly ultramafic.

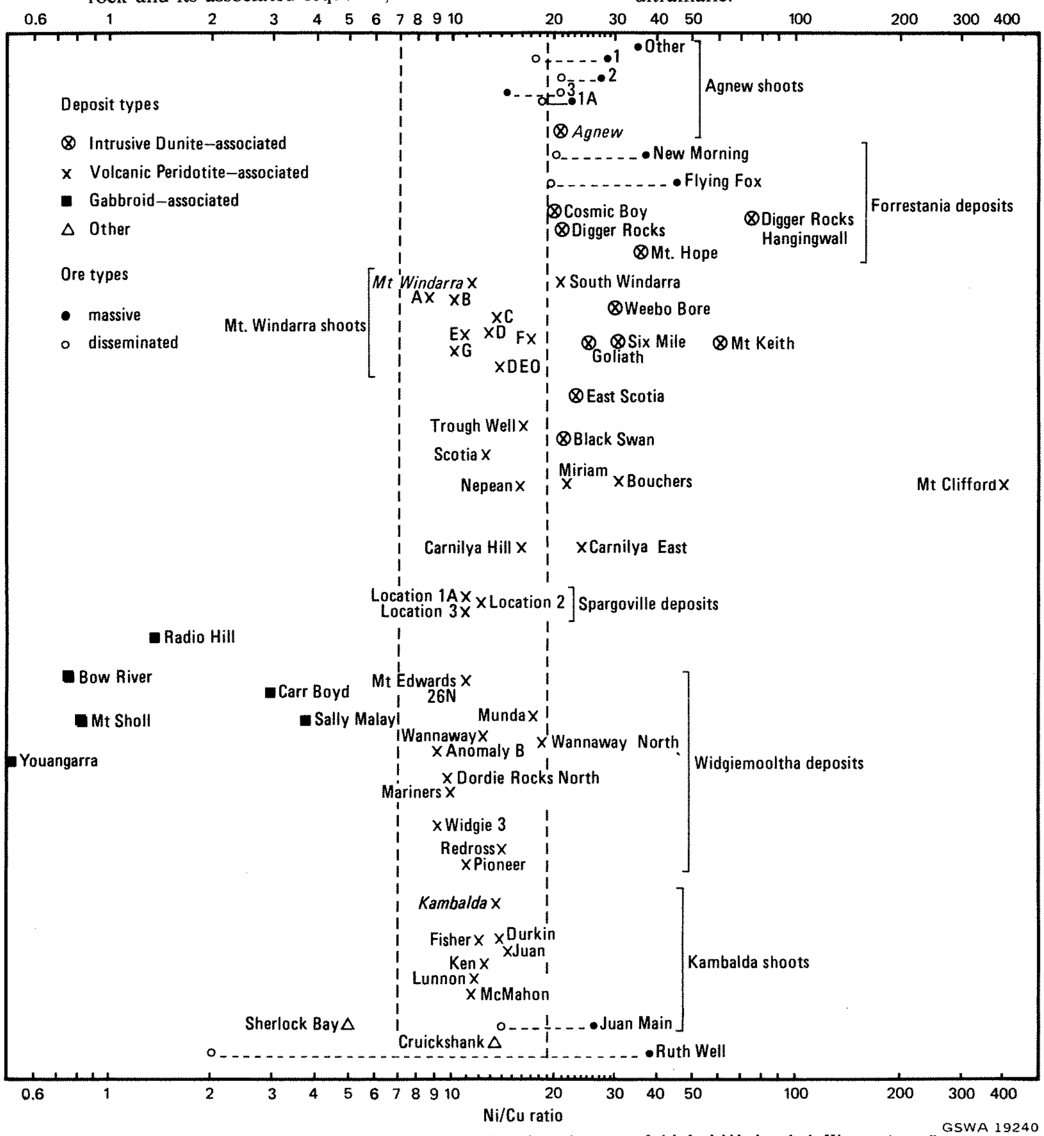


Figure 14. Mean bulk Ni/Cu ratios (calculated from resource data) for various types of nickel sulphide deposits in Western Australia. The mean values for a group of deposits are indicated by names in italics.

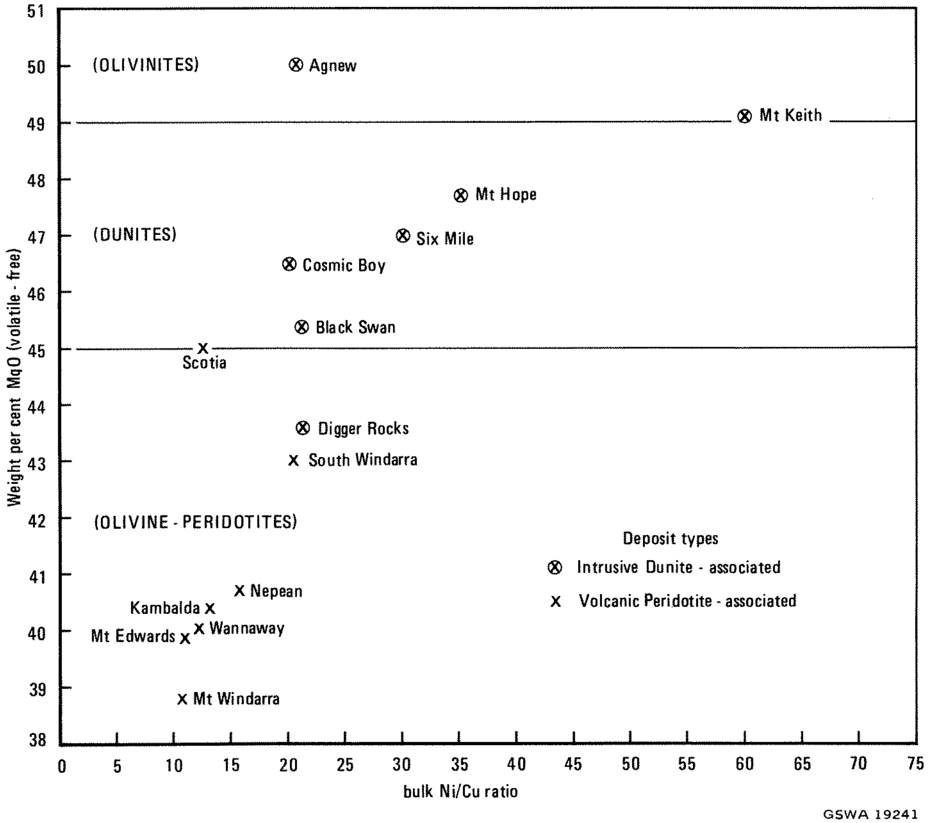


Figure 15. Plot of bulk Ni/Cu ratios for nickel sulphide deposits versus MgO content (volatile-free) of ultramafic host rocks.

(4) *Layered sedimentary-associated deposits* (e.g. Sherlock Bay).

(5) *Vein-type arsenical deposits* (e.g. Mount Martin).

Criteria (i) and (iv) define deposits of types (1) to (3), and criteria (v) and (vi) define deposits of types (4) and (5). The relationship between type of deposit, basicity (expressed as MgO content), and Ni:Cu ratios is illustrated by Figures 14 and 15. As discussed in Chapter 2 this relationship is probably a fundamental one controlled by the magmatic differentiation of mafic to ultramafic magmas and their contained sulphide-oxide liquids. The host rocks with higher magnesia contents generally contain mineralization impoverished in copper compared with mineralization in less magnesian rocks (Fig. 15). It is important to consider the *bulk* nickel and copper content of the deposit as massive sulphides are commonly depleted in copper compared with disseminated sulphides (Fig. 14).

INTRUSIVE DUNITE-ASSOCIATED DEPOSITS

Deposits of this type are generally contained in olivine-rich ultramafics with magnesia contents of more than 45 per cent, and have bulk Ni:Cu ratios greater than 19.

The host rocks range in composition from olivine peridotite to olivinite, a rock consisting originally almost totally of close-packed olivine crystals, which on the basis of olivine of Fo_{92} composition may contain up to about 51 per cent magnesia. Several host units may exhibit marginal or lateral (along strike) phases which are of olivine peridotite, peridotite or less magnesian composition. Though most dunitic hosts are thought to be intrusive, the evidence for this may only derive from detailed mapping and drilling. Olivine-rich ultramafic units may be semi-continuous for tens of kilometres along strike, but the mineralized dunitic to olivinitic portions tend to be podiform bodies several hundred metres thick, with strike extent limited to a few kilometres. Most units are generally conformable with the country rocks and are therefore strictly sills, though some may have been emplaced into already vertical or steeply inclined supracrustal belts.

The bulk Ni:Cu ratios are consistently greater than 19 (Fig. 14). Individual parts of weakly disseminated deposits may be very nickel-rich in mineralogy, though this may be partly the result of metamorphic adjustments (see Chapter 2). The Agnew deposits appear to be abnormally copper-rich in relation to the very magnesian nature of the ultramafic host (Fig. 15).

The resources of this type of deposit are large because much of the mineralization is low-grade disseminated sulphide with bulk nickel contents being from 0.5 to 1.0 per cent (e.g. Six Mile, Mount Keith, Weebo Bore, Black Swan). Several deposits of this grade contain between 0.1 and 1.0 Mt of nickel metal, and under favourable economic conditions would be amenable to open-cut mining. Agnew is again a notable exception, containing large tonnages of medium-grade disseminated ore averaging 1.84 per cent nickel which are to be exploited by conventional underground mining. Resources of massive sulphide ores occur at Agnew and Forrestania where bulk nickel grades are in the range of 3 to 5 per cent and the amount of contained nickel in individual deposits is up to about 0.1 Mt. Massive sulphides generally occur marginal to disseminated sulphides or separated from the ultramafic in faults and shears in the country rocks.

VOLCANIC PERIDOTITE-ASSOCIATED DEPOSITS

Most deposits of this type are contained in olivine peridotites with magnesia contents in the range 38 to 45 per cent, and have bulk Ni:Cu ratios from 7 to 19.

In contrast to the dunite-associated deposits, the host ultramafic is an integral part of a mafic to ultramafic volcanic sequence and is commonly found at or near the stratigraphic base of the sequence. The ultramafic host is thinner than the average dunitic host, it is commonly less than 50 m thick and rarely up to 150 m thick (e.g. Juan Main shoot, Kambalda). It is of limited extent and lensoid or podiform in shape, in similar fashion to the dunitic host. Unlike the dunitic host, the olivine peridotite host unit is typified by an asymmetric mineralogical and geochemical vertical profile, which is comparable with less magnesian komatiitic ultramafic flows (Pyke and others, 1973; Barnes and others, 1974) and implies the operation of gravity-induced differentiation during emplacement. The upper, spinifex-textured parts of such flows are commonly not well developed in the olivine peridotite hosts, and where present are very thin (up to a few metres), compared with the total thickness of the host unit. The evidence from the better known areas suggests that the peridotite hosts represent volcanic *flows* rather than subvolcanic sills.

Bulk Ni:Cu ratios fall within a restricted range (Fig. 14). Some deposits with abnormally high ratios (e.g. Mount Clifford) have features which suggest transition between the dunite- and peridotite-associated types of deposit. In other cases the mineralization making up the resources may have lost copper because of segregation into chalcopyrite-rich veins in the barren wallrocks (e.g. Miriam and Bouchers), or this mineralization is largely copper-deficient massive sulphide (e.g. Carnilya East). The South Windarra deposit has a slightly higher ratio of 20.6, but this seems consistent with the magnesia-rich composition of the ultramafic host (Fig. 15).

Total resources of this type of deposits are less than the resources of intrusive dunite-associated deposits, but the bulk nickel grade is mostly between 1 and 4 per cent, with the currently producing mines having head grades between 2 and 4 per cent Ni. This reflects the greater proportion of massive sulphide making up the deposits. Individual deposits are small, 30 000 t of contained nickel being typical. In several deposits there is little mineralization present which assays between 0.5 and 1.0 per cent Ni; the 1 per cent cut-off figure commonly used in reserve calculations corresponds to a natural, abrupt decline in sulphide and consequently in nickel content (e.g. Kambalda). A vertical zonation of sulphides characterizes most deposits: basal massive ore is overlain by matrix or disseminated ore which may become less sulphidic upwards. This feature can also be interpreted in terms of gravity differentiation of the sulphidic ultramafic flow during its emplacement onto a sub-horizontal surface.

In detail, the ore is complexly distributed and requires careful small-scale mining which mostly precludes the use of open stoping and bulk extraction.

GABBROID-ASSOCIATED DEPOSITS

These deposits occur in layered, multiple intrusions consisting dominantly of gabbroidal rocks accompanied by subordinate olivine-rich ultramafic rocks, peridotite, pyroxenite, and anorthosite. The intrusions may be of tholeiitic or komatiitic affinity. Evidence for gravity differentiation in the form of igneous layering is common. Minor occurrences are known from the Proterozoic Jimberlana Dyke. The bulk Ni:Cu ratios of the deposits are less than 7, declining to below unity. Although there are few deposits of this type, it appers that those with a higher Ni:Cu ratio tend to have a higher absolute nickel grade. For example the Carr Boyd deposits have a mean Ni:Cu ratio of about 3 and a mean Ni grade of 1.5 per cent, whereas at Mount Sholl the figures are 0.83 and 0.5 per cent respectively.

In common with some of the thick dunite to olivinite host units, the igneous rocks comprising the gabbroid intrusions were generally incompletely recrystallized and hydrated during regional metamorphism. The rocks specifically containing sulphides are varied, including gabbro, norite, pyroxenite, bronzitite, pyroxenite breccia and peridotite. Mineralization in a single intrusion may occur in more than one rock type. The style of mineralization in the previous two types of deposit can be regarded as stratabound, but this only applies in part to the gabbroid-associated type, and specifically to most of the disseminated sulphides. Discordant lenses or pipe-like bodies of breccia sulphides (igneous and country rock inclusions in a sulphide matrix) are a feature of this type (e.g. Sally Malay, Carr Boyd).

Total resources of this type of deposit are small, and bulk nickel grades are less than 2.5 per cent. This reflects the paucity of massive ore and the small, irregular shape of ore shoots, particularly the discordant bodies of breccia sulphides. Individual deposits are small, only rarely exceeding 30 000 t of contained nickel. The complexity and irregularity of the deposits makes mining difficult and costly.

LAYERED SEDIMENTARY-ASSOCIATED DEPOSITS

Deposits of this type are rare, one being the Sherlock Bay deposit in the west Pilbara Block. The other deposits tentatively identified as being of this type are the Cruickshank deposit, south of Kambalda, and F Shoot at Mount Windarra. In all examples disseminated sulphides occur in stratiform layers in bedded metamorphic rocks of unusual mineralogy which are probably of sedimentary-exhalative origin. The host rock at Sherlock Bay is possibly a metamorphically modified carbonate-facies banded iron-formation (Groves and others, 1978), present in an ultramafic to felsic tuffaceous sequence intruded by podiform metaperidotite. The Cruickshank deposit is at the base of a thin (90 m) ultramafic sequence occurring between two metabasalt units (McDonald, 1976). The host rock overlies sulphidic chert and slate and consists mainly of amphibole, quartz, carbonate and chlorite, but may contain thin layers of chert. The host rock at F Shoot, Mount Windarra is within the ultramafic sequence and resembles that at Sherlock Bay in some respects.

The deposits are small with bulk nickel grades of 0.52 per cent for Sherlock Bay, 1.75 per cent for Cruickshank, and 1.87 per cent for F Shoot. Bulk Ni:Cu ratios are 5, 13 and 17 respectively, the value for Cruickshank being similar to that for the volcanic peridotite-associated deposits at Kambalda-St Ives.

VEIN-TYPE AURIFEROUS-ARSENICAL DEPOSITS

These deposits are also rare; detail is available for two of them but all are associated with gold mineralization. At Mount Martin, south of Kalgoorlie, a complex system of quartz-carbonate-sulphide-arsenide veins occurs in metasedimentary rocks near a contact with ultramafic rocks. The mineralization at Bamboo in the east Pilbara Block consists of disseminated nickel arsenides in silicified and brecciated, dolomitized ultramafic at its contact with chlorite-dolomite schist. Some of the veins at Mount Martin are auriferous but are rarely both nickel- and gold-bearing, whereas the gold mineralization at Bamboo is not coincident with the nickel mineralization. The deposits are very small in terms of contained nickel and are unlikely to be developed.

LATERITIC DEPOSITS

Lateritic nickel deposits form by the deep weathering and ferruginization of olivine-rich ultramafic rocks which are generally devoid of sulphides. In general terms concentrations of elements are distributed through the weathered profile according to their respective geochemical mobilities. In an idealized profile silica and magnesia show the strongest depletion upwards in relation to bedrock contents. Nickel is enriched in the lower part of the profile where hydrolysis of olivine and pyroxene gives rise to saprolitic clays containing hydrous nickeliferous silicates (Table 12) and showing the morphology of the original minerals. Nickel grades may also be enhanced in the upper iron-oxide-bearing (ferruginous) part of the profile, particularly where mottled clays are present near the contact zone with the underlying saprolite.

The weathering history of ultramafic rocks in the State is complex (see Chapter 2), and secondary silica present at high and/or low levels in the profile is a common feature. The saprolitic part of the profile is partly silicified in many examples. Nickel concentrations occur in both the saprolitic and ferruginous parts of the profile in Western Australia. Medium- to coarse-grained dunite and olivinite form the bedrock of the important deposits of the Yilgarn Block (Bandalup, Murrin, Ora Banda, Pyke Hill) whereas pyroxenite and dunite occur below the deposits at Wingelinna in the Musgrave Block.

Bulk nickel grades are generally in the range 0.9 to 1.4 per cent representing a concentration of between three and five times the nickel content of bedrock. Several deposits possess resources of around 1 Mt of contained nickel. Discontinuities in bedrock structure, such as dolerite dykes, granite contacts, or faults, are important in determining the sites of greatest nickel enrichment (e.g. 2 to 3 per cent Ni) within a given deposit. Cobalt is the only other element of potential economic importance in lateritic nickel deposits. At Wingelinna, for example, demonstrated resources of 56 Mt average 1.24 per cent Ni and 0.087 per cent Co (Ni: Co = 14). Local cobalt enrichments in the Ora Banda deposit have an average grade of 0.1 per cent Co, attaining about 1 per cent Co in small patches which are also enriched in nickel and maganese.

CHAPTER 4

Intrusive dunite-associated deposits

SUMMARY OF GEOLOGY AND MINERALIZATION

DISTRIBUTION

Important examples of this type of deposit are mainly located in the northern third of the Norseman-Wiluna belt (north of Leonora) and in the southern quarter of the Southern Cross - Forrestania supracrustal belt (Plate 1). Isolated, small deposits occur at Ravensthorpe, Lake Johnston, southwest of Coolgardie, and east and northeast of Kalgoorlie. In terms of pre-mining contained nickel resources at 1 per cent nickel cut-off, 68 per cent of the mineralization is accounted for by the Agnew (Perseverance) deposit, 21 per cent by the Forrestania group and the remainder by the Honeymoon Well (8 per cent), Sir Samuel (2 per cent), and Ravensthorpe (1 per cent) deposits. If the cut-off figure is lowered to 0.4 per cent nickel, the contained nickel resource increases from 1.35 Mt to 4.23 Mt and the Agnew and Mount Keith deposits each account for 37 per cent of the total, with the remainder largely being contained in the Six Mile and Melon deposits. However, this calculation does not include the substantial mineralization at Forrestania which averages less than 1 per cent nickel.

The distribution of important resources of intrusive dunite-associated mineralization is accordingly more restricted than that of volcanic peridotite-associated mineralization. Moreover, these two types of mineralization are rarely geological associated with one another. The following geological features are considered to be of potential importance in explaining the distribution of intrusive dunite-associated deposits:

1. the presence of essentially concordant thick lenses of cumulus-textured olivine-rich ultramafic rocks (olivine peridotite to olivinite composition);
2. the association of such lenses with clastic sedimentary and felsic volcanic rocks in the footwall and volcanic ultramafic rocks in the hangingwall; and
3. the association of such lenses with persistent strike faults, ductile shear zones or tectonic lineaments in narrow, gently curvilinear supracrustal belts.

In common with probable controls of the volcanic peridotite-associated deposits the strike faults are regarded as the most important feature, because they are interpreted as reflecting deep-seated and temporarily persistent zones of crustal (and possible upper mantle) weakness. However, this conclusion makes the lack of spatial correlation between the two deposit types more difficult to comprehend.

STRATIGRAPHY AND STRUCTURE

These two aspects of the geology are often difficult to separate when dealing with narrow, strike-faulted supracrustal belts which are generally poorly exposed and are characterized by steep dips. Nevertheless certain lithological associations that include the mineralized olivine-rich ultramafic lenses consistently emerge when most deposits are considered. Naldrett and Turner (1977) from a study of deposits of the Yakabindie group, first suggested that the mineralized lenses could be stratigraphically controlled. They suggested that mineralized lenses at Yakabindi, Agnew and Mount Keith are all situated at or near contacts between felsic clastic metasediments and stratigraphically overlying ultramafic flows and metabasalts. The present regional study supports this contention and demonstrates that a similar control is probable for several other deposits in the Norseman-Wiluna belt and for most deposits in the Forrestania group and at Ravensthorpe. In some lenses Donaldson (pers. comm., 1979) has found cryptic layering defined by igneous olivine compositions which he interpreted as developed in subvolcanic sills.

Naldrett and Turner (1977) went on to suggest that the olivine-rich ultramafic lenses at Yakabindie represent the subvolcanic feeders for the overlying ultramafic volcanic piles. If this is the case then the lenses should have been folded and internally deformed along with their country rocks; available evidence is confirmatory for the Yakabindie and other deposits. At Forrestania the olivine-rich ultramafic lenses appear to be repeated by a faulted, major synclinal structure. The component rocks of the lenses generally show little evidence of deformation in the hand specimen, but pervasive fracturing and granulation of the olivine or serpentine aggregates is commonly seen under the microscope. The marginal parts of the lenses or zones subjected to talc-carbonate alteration may be well foliated. In contrast to the bulk of the lenses, the country rocks commonly display dynamic metamorphic textures, but this difference can probably be attributed to the differing response to strain of the competent unlayered rocks of the lenses versus the generally incompetent layered country rocks.

A stratigraphic interpretation of the distribution of the lenses is at variance with Burt and Sheppy (1975) and Binns and others (1976, 1977) who regarded them as dyke-like intrusions. For the Wiluna-Agnew area, Binns and others (1976) also stated that the intrusions postdate early deformation phases in the supracrustal belt. Although the later intrusion of some dunitic lenses cannot be precluded, especially if the associated strike faults are such fundamental planes of weakness as is supposed, it is suggested that the bulk of the mineralized lenses were emplaced penecontemporaneously with the volcanic sequences.

The size of the olivine-rich ultramafic lenses is variable. Strike length typically ranges from 500 to 10 000 m and the maximum thickness from 50 to 1 100 m. The down-dip or down-plunge extent of most lenses is unknown: the Perseverance ultramafic body at Agnew is 6 000 m long, up to 700 m thick and at least 1 100 m in vertical extent. Many lenses are zoned, having a core of dunite-olivinite, which may or may not be serpentinized, and an envelope of generally less magnesian (but invariably serpentinized) rocks ranging from pyroxenite to olivine peridotite in composition. Some of these less magnesian rocks have rounded olivine pseudomorphs in a finer grained matrix giving rise to a 'sago-like' texture. In some centres (Yakabindie, Mount Keith, Forrestania) the lenses of olivine-rich ultramafic rock are within narrow zones of peridotitic rocks which are far more extensive than the lenses themselves.

Essentially unserpentinized cores to the lenses are present at Agnew, Betheno and in the Forrestania region (e.g. Digger Rocks, Mount Hope). The rock type in the cores is a nearly monomineralic aggregate of close-packed, polygonal to subequant olivine grains 5 to 10 mm in diameter, which have a composition of 87 to 95 mole per cent forsterite and typically contain 0.37 weight per cent nickel in solid solution (Binns and others, 1977). Chromite is the only important accessory. The olivine is commonly colourless and appears to be igneous olivine which has been reheated during regional metamorphism; anthophyllite porphyroblasts may be superimposed on the olivines in rocks from high grade metamorphic terrain (e.g. Agnew, Forrestania). The texture of the olivine aggregate is faithfully preserved in many serpentinized rocks of dunite to olivinite composition. Partial hydration of the igneous olivine followed by metamorphic dehydration leads to the development of interlocking blades of prismatic metamorphic olivine (commonly accompanied by talc) in high-grade metamorphic terrains. Progressive changes in metamorphic mineralogy are discussed by Binns and others (1976, 1977) and summarized in Table 8. Conversion to talc-magnesite rocks affects parts of many lenses.

There appears to be little difference between the chemistry of the unaltered versus altered dunite-to-olivinite rocks when comparison is made on a voltile-free basis (Table 15). The magnesia content ranges from 45 to 51.5 per cent, and titania (0.01 to 0.06 per cent), and alumina plus lime contents (0.2 to 2.4 per cent) are typically very low compared with the host rocks of volcanic peridotite-associated deposits (Table 15), as pointed out by Binns and others (1977).

TABLE 15. AVERAGE CHEMISTRY OF METAMORPHOSED DUNITE-OLIVINITE ROCKS IN LENSES AND OLIVINE PERIDOTITE IN MINERALIZED FLOWS

Weight per cent	A	B	C
SiO_2	41.7	41.0	45.7
TiO_2	0.02	0.01	0.21
Al_2O_3	0.57	0.14	3.1
Cr_2O_3	0.28	0.21	0.54
FeO(t)	7.8	7.3	8.8
MnO	0.09	0.11	0.13
MgO	49.2	50.9	40.0
CaO	0.24	0.16	1.5
Na_2O	0.04	0.03	0.05
K_2O	0.01	0.01	0.08
P_2O_5	0.02	0.02	0.02
$CaO:Al_2O_3$	0.4	1.1	0.5
$Al_2O_3:TiO_2$	28	14	15

Notes:

1. Column A is the average of 50 serpentinites, talc-carbonate and olivine-talc rocks in the dunitic lenses containing nickel sulphides.
2. Column B is the average of 8 essentially unserpentinized olivinites from the cores of dunitic lenses at Agnew, Betheno and Mount Hope (Forrestania).
3. Column C is the average of 58 serpentinites and talc-carbonate rocks from mineralized olivine peridotite flow units at Kambalda (Lunnon shoot), Mount Windarra, Scotia, Carnilya Hill, Nepean, Spargoville, Mount Edwards and Wannaway.
4. Analyses recalculated free of volatile components and nickel.
5. Total iron expressed as ferrous oxides.
6. Data from Binns and others (1977).

MINERALIZATION

Nickel deposits related to intrusive dunites show a wide range in the size of their contained nickel resources but a small range in bulk nickel tenor (Fig. 16). There does not seem to be any relationship between deposit size and bulk nickel tenor. The physical dimensions of deposits are generally in approximate proportion with the dimensions of the host olivine-rich ultramafic lenses: many deposits are found in the thickest part of the lens. The largest deposits in terms of contained nickel (categories 1 and 2 in Fig. 16) have strike lengths in the range 500 to 2 000 m and maximum thicknesses of 25 to 320 m, but the largest dimensions apply to the deposits of bulk tenor below 1 per cent nickel (e.g. Mount Keith, Six Mile).

For mineralization which averages more than 1 per cent nickel, the main control of the bulk tenor of the deposit is the proportion of massive and breccia ores (deformed rock fragments in a sulphidic matrix) to less sulphidic ores, rather than the nickel content of the sulphide fraction. Thus all deposits with bulk nickel tenors of more than 1.9 per cent contain important amounts of massive and breccia ores, which are concentrated marginally, at or near the stratigraphic base of the host ultramafic lens. Breccia ores are also found as lenses and veins remobilized into faults and fractures within disseminated ore, barren ultramafic or metasedimentary country rocks.

Disseminated sulphides, which make up the bulk of the nickel resource in all except the highest grade deposits, can be divided into low-grade (0.4 to 1.0 per cent nickel) and high-grade (1.0 to 4.0 per cent) varieties that are mainly a function of the volume of sulphide present. The high-grade disseminated sulphides are best developed marginally to the host lenses, and are therefore associated with the massive and breccia ores. The low-grade disseminated sulphides are commonly found either in the cores of the lenses or passing downwards into high-grade disseminated sulphides.

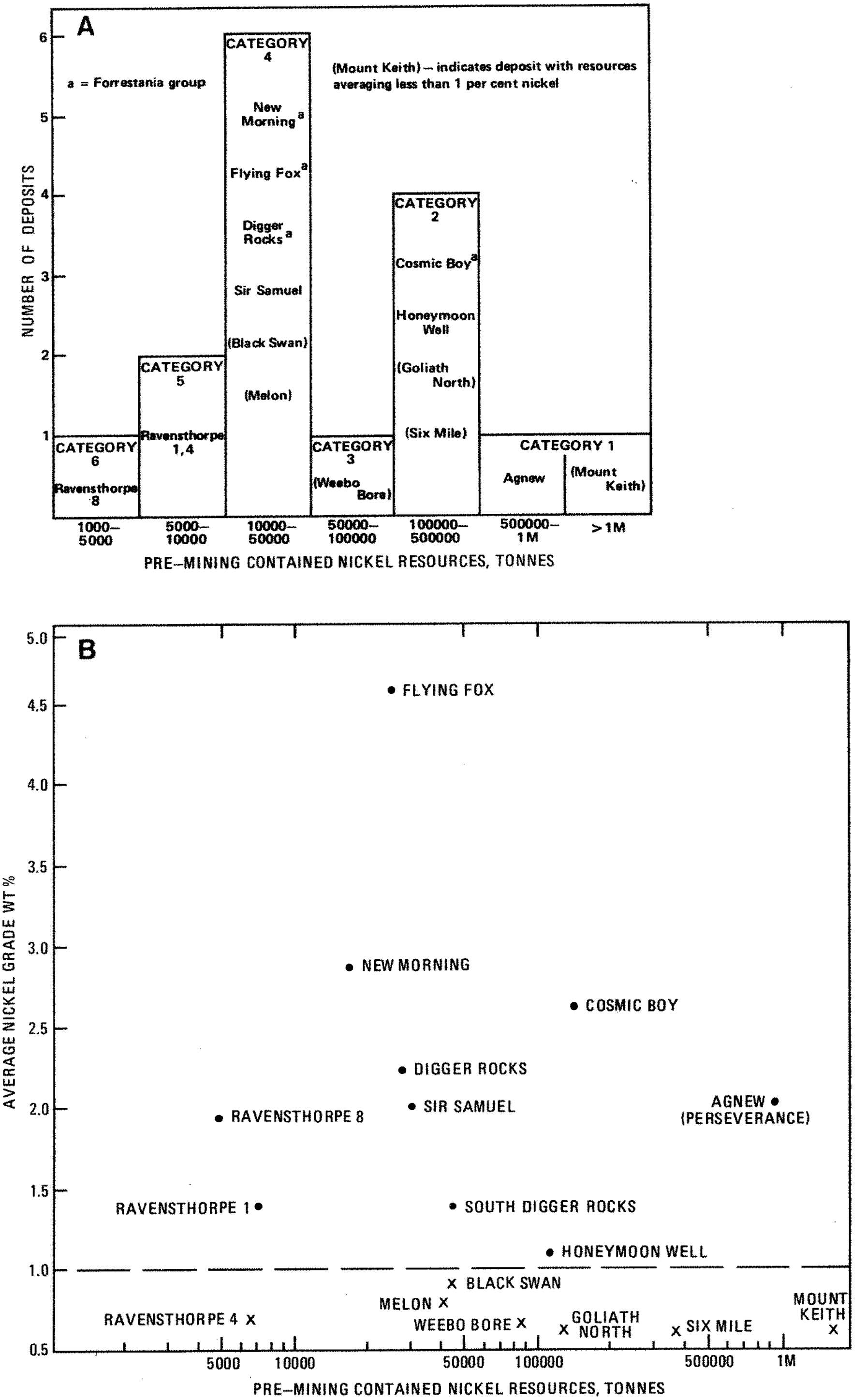


Figure 16. A. Histogram of the number of intrusive dunite-associated deposits in defined categories based on pre-mining, contained nickel resources (tonnes).
B. Plot of average nickel grade (weight per cent) versus pre-mining contained nickel resources (tonnes) for intrusive dunite-associated deposits.

The common opaque mineralogy of high-grade disseminated, matrix, breccia and massive ores, is (in order of decreasing abundance): pyrrhotite, pentlandite, magnetite, pyrite, chalcopyrite and chromite (or valleriite). In low-grade disseminated sulphides additional or alternative phases present are: millerite, heazlewoodite, godlevskite, polydymite, vaesite, awaruite, bravoite, cobaltite, siegenite, nickeliferous linnaeite and cubanite. Iron and nickel arsenides are locally present, particularly in talc-carbonate host rocks.

Discounting the low-grade disseminated sulphides, the amount of nickel in the sulphide fraction is largely determined by the pyrrhotite: pentlandite ratio. In many ore bodies this ratio appears to be higher for the more sulphidic ores, so that massive sulphides containing more than about 9 per cent nickel are rare, but those containing about 6 per cent are common. For the low-grade disseminated sulphides, even though the overall nickel content is low, the amount of nickel in the sulphide fraction may attain 40 per cent because of the dominance of nickel-rich sulphide phases such as pentlandite, millerite and heazlewoodite.

Bulk Ni:Cu ratios are greater than 19. However, there may be considerable variation within a single deposit. Massive, breccia, and low-grade disseminated sulphides tend to have higher Ni:Cu ratios than high-grade disseminated sulphides (e.g. Agnew, Forrestania). Information on bulk Ni: Co ratios is sparse but available data gives a mean of 46 (standard deviation 13). Palladium and, to a lesser extent, iridium increase in amount in proportion to the nickel tenor (Keays and Davison, 1976).

GENESIS

As yet there has been little consideration in the literature of the genetic aspects of intrusive dunite-associated deposits. This stems from their late discovery, so that not until the mid-1970s were the deposits being referred to as a separate class (e.g. Travis and others, 1976; Binns and others, 1977). Poor exposure and deep chemical weathering are further impediments to an understanding of these deposits.

In common with volcanic peridotite-associated deposits, ore formation from an immiscible Fe-Ni + Cu sulphide liquid of magmatic origin is considered to be the fundamental process. The association of sulphides with olivine-rich rocks indicates a strong link between fractionating komatiitic magma and the accumulation of original sulphide melt. However, modification of original magmatic sulphides by tectonometamorphic processes may be important and this should be considered before erecting magmatic models.

Nickel sulphides (dominantly pentlandite) are present in essentially unserpentinized dunite-olivinite in the cores of mineralized olivine-rich ultramafic lenses; such sulphides are regarded as magmatic (Binns and others, 1977; Groves and Keays, 1979). Accordingly, study of the changes in these sulphides in the progressively altered envelopes of such lenses is instructive. This has been done for low-grade disseminated sulphides at Betheno, Mount Keith and Black Swan, where the end result of alteration appears to be a possible increase in the amount of iron sulphide, but with no important change (or even a decrease) in the overall amount of nickel in the sulphides (Groves and Keays, 1979; Keays and others, in prep.). Mineralogical changes to low-grade sulphide assemblages may be substantial, but Donaldson (1980) concluded that the alteration processes have been largely isochemical for nickel on a hand-specimen scale, and that there is no evidence for nickel loss from silicate phases on a scale necessary to produce a metamorphic deposit. In the case of the high-grade disseminated sulphides at Agnew, there are few important changes in the mineralogy of the sulphides from dunite-olivinite to serpentinite, and Hudson (pers. comm., 1979) has found no marked difference in the chemical composition of the respective sulphide fractions.

Physical modification of magmatic sulphides in volcanic peridotite-associated deposits is discussed in the first part of Chapter 5, and though there is much less information (particularly underground observations) for intrusive dunite-associated deposits, similar processes and effects can be envisaged (see Chapters 3 and 5 for details). Metamorphic recrystallization involving intergrowth of metamorphic silicates and sulphides is common for low-grade disseminated sulphides, but may be both lacking in some high-grade disseminated ore and well-developed in the form of triangular-textured ore (sulphides interstitial to bladed metamorphic olivine/serpentine) in other parts of the same deposit (e.g. Agnew, Forrestania). Homogenization and separate deformation of low-strength massive ore during regional metamorphism has occurred in a similar manner to that described in more detail for volcanic peridotite-associated deposits (Chapter 5). The most conspicuous product of these processes is breccia ore (e.g. Agnew, Forrestania, Mount Keith-Cliffs-Charterhall). Segregation and/or diffusion of copper from massive ore during metamorphism probably accounts for higher Ni:Cu ratios for massive ore compared with disseminated ore.

The above discussion has assumed the existence of high-grade disseminated and massive ores before regional metamorphism. This is based on the concentration of such ores on one side of the olivine-rich ultramafic lenses and the lack of ores transitional between dissemintated and massive ores. On the other hand, Binns and others (1977) considered secondary segregation and enrichment of less sulphidic ores during tectonism and regional metamorphism a likely process in the more deformed margins of lenses, whilst noting that high-grade deposits are restricted to mid- to high-amphibolite facies metamorphic domains. However, if some of the lenses were emplaced as stratigraphically controlled sills, as discussed above, then basal magmatic segregations would be expected in the case of peridotitic crystal mushes rich in droplets of sulphide liquid (see Wilson and others, 1969). Such a mechanism was envisaged by Martin and Allchurch (1975) for the Agnew deposit.

The bulk Ni:Cu ratios of the deposits are consistent with the expected partition of nickel and copper between a sulphide melt and a silicate melt of a composition (32 to 33 per cent MgO) likely to be associated with residual accumulations of forsteritic olivine (Naldrett and Turner, 1977; Duke and Naldrett, 1978). Therefore, a strong genetic link between fractionating komatiitic magmas and associated nickel ores is indicated. The sulphide melt was

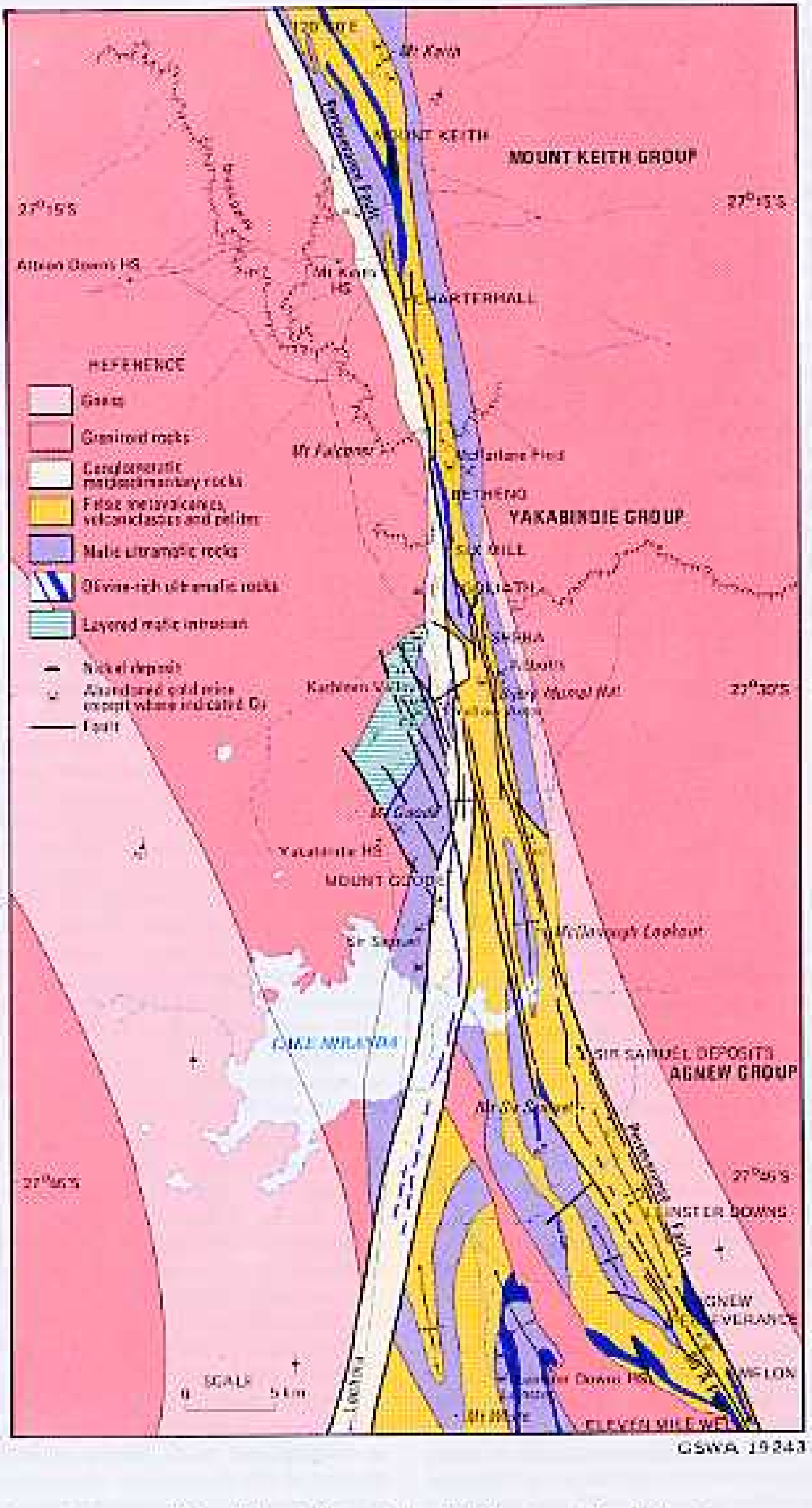


Figure 17. Geological map of the Agnew — Mount Keith region showing location of nickel deposits and olivine-rich ultramafics.

effectively trapped by the olivine-rich residuum (estimated at 80 to 90 per cent phenocrysts) and was not extruded with any of the picritic to peridotitic liquids which reached the surface. This trapping is necessary to explain the apparent general lack of any associated mineralized ultramafic flows. It is not apparent why this confinement of sulphide liquid was so effective, as some of the volcanic peridotite-associated deposits occur in flow units which contained 60 to 70 per cent olivine phenocrysts.

The bulbous, lenticular shape of many lenses is considered to be largely original, and the expected shape for a subvolcanic magmatic chamber. However, some lenses could represent boudinaged remnants of formerly more uniform and continuous bodies. The coincidence of mineralization, especially basal concentrations, with the thickest parts of the lenses suggests that depressions in the floor of the chamber acted as traps for segregating sulphidic liquid. Surface depressions were also important traps for sulphidic liquid in the volcanic peridotite-associated deposits. Irregularities in the walls of dykes could also function as traps for sulphidic liquids. Low-grade disseminated sulphides in the cores of olivine-rich ultramafic lenses perhaps indicate that sulphur saturation was only achieved after considerable olivine fractionation in the chamber had taken place. On the other hand centrally disposed sulphides and marginal peridotites (e.g. Mount Keith) are also suggestive of dynamic emplacement of a sulphide-bearing crystal mush in a dyke-like body. It is possible that both dyke- and sill-like processes were important in the formation of this type of deposit.

AGNEW GROUP

GEOLOGY

GENERAL

The nickel deposits of the Agnew group (Agnew, Eleven Mile Well, Leinster, Melon, Sir Samuel) occur in the northern part of the Norseman-Wiluna belt in a region characterized by many branching strike faults, ductile shear zones and/or lineaments (Fig. 17). The deposits are located in a zone of steeply inclined, lenticular, olivine-rich ultramafic rocks which lie parallel to the Perseverance Fault.

Exploration in the area has been carried out mainly by Selco (or W. Selcast) since 1964, with lesser work by Kennco, WMC and others. The main period of exploration activity was from 1969 to 1974, highlights being the discovery of the Mount Keith deposit to the north in 1969 which stimulated intensive exploration along strike, and the discovery of the Agnew (Perseverance) deposit in 1971. Most of the geological data relevant to nickel mineralization stems from work by Selco geologists as reported by Allchurch (1974), Martin and Allchurch (1975), and Milne and Mason (1975). The regional geology is described by Bunting and Williams (1979). Specialized studies of aspects of the Agnew deposit have been carried out by Nickel and others (1977) and Binns and others (1977), and petrological work by D.R. Hudson is in progress.

Regional metamorphism attained upper amphibolite facies conditions (600-650°C, 300 to 500 MPa) as deduced by Binns and Groves (1976). Dynamic metamorphic textures are typical in general but static to dynamic igneous and overprint features are characteristic of the metamorphosed olivine-rich ultramafics in particular.

STRATIGRAPHY AND STRUCTURE

Poor outcrop, numerous strike faults, and tightly appressed, locally overturned folds make it impracticable to erect a stratigraphic scheme with any confidence. It appears that all the deposits of the group occur within one lenticular zone of olivine-rich ultramafic rock, which is that closest to the Perseverance Fault, although northwards from the Agnew deposit lenses of less magnesian ultramafic rocks are generally interposed between this zone and the fault. The olivine-rich ultramafic zone (Perseverance ultramafic lens) is interpreted to be on the eastern, overturned, west-dipping limb of an anticline which strikes north-northwest and is inclined steeply westwards (Martin and Allchurch, 1975). Strike faults, named the Perseverance Fault to the east and the 60A Fault to the west, appear to bound the anticline laterally and severely attenuate it from the vicinity of the Agnew deposit southwards. North-plunging folds in recrystallized chert near Mount Sir Samuel indicated that the anticline plunges out to the north-northwest, but a fault-bounded anticlincal zone is maintained by the presence of another *en echelon* anticline (at McDonough Lookout) which has a core of amphibolite (Fig. 17).

To the west of the 60A Fault is a tapering strip of mafic (including pillowed metabasalt, metadolerite and chert) and minor ultramafic rocks in which Martin and Allchurch (1975) identify an asymmetrical syncline plunging gently northwest. Bunting and Williams (1979) suggested that these mafic rocks may correlate with similar mafic rocks occupying a syncline at Mount White, and that the feldspathic, micaceous metasedimentary rocks between the Agnew deposit and Mount Sir Samuel may equate with like rocks below the Mount White mafic sequence. A more tenuous correlation, using the regional data of Williams (1976), results in the mafic rocks west of the 60A fault being equivalent to the second (mineralized) mafic-ultramafic sequence in the southern half of the Norseman-Wiluna belt (Bunting and Williams, 1979).

The structural sequence of rock types encountered in the inclined anticline at the Agnew deposit (Fig. 18) is summarized in Table 16 and variations along strike are noted below. Traced northwards the Perseverance ultramafic lens thins rapidly to a unit less than 20m thick 600m north of Perseverance Bore, but some 200m to the east there is another ultramafic unit about 30 to 40m thick. This ultramafic unit appears to be mainly of picritic to peridotitic composition (talc-chlorite and amphibole-chlorite) until the area of Leinster Downs prospect is reached, west of McCarthy Bore. Here an ultramafic unit 50 to 150 m thick develops and includes weakly mineralized medium to coarse-grained partly foliated serpentinized dunite-olivinite of the Perseverance ultramafic type. Foliated quartz-biotite-hornblende metasedimentary rocks containing variable quantities of pyrite, pyrrhotite, magnetite,

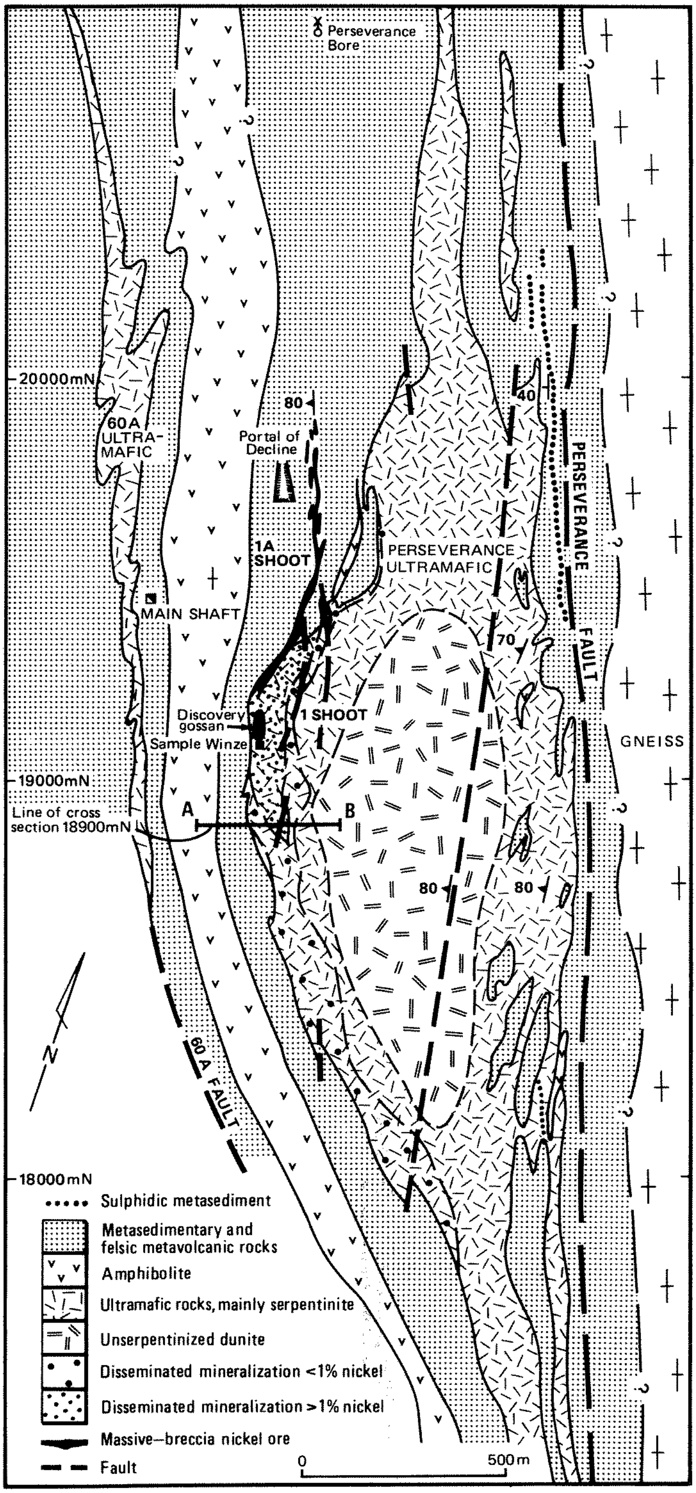


Figure 18. Geological map (subcrop) of the Agnew (Perseverance) deposit, based on Allchurch (1974).

carbonate and garnet, separate this olivine-rich ultramafic unit from a unit of amphibole-chlorite rock 150 to 250 m to the west, and form the dominant country rock.

TABLE 16. STRUCTURAL ROCK SEQUENCE AT THE AGNEW (PERSEVERANCE) DEPOSIT

Unit	Lithology	Thickness (m)
WEST (60A Fault)		
60A ultramafic	Foliated talc-carbonate-chlorite rock alternating with granular serpentinite and metasediment; coarse bladed metamorphic olivine pseudomorphs	10-130
Metasediment and felsic meta-volcanic	Layered and foliated, fine-grained granofelsic quartz, plagioclase and K-feldspar rocks with lesser biotite, muscovite, chlorite, hornblende and almandine; megacrysts of quartz, feldspar, almandine	50-140
Un-named	Sulphidic black slate or chert	1-10
Amphibolite	Coarse-grained, poorly foliated hornblende/cummingtonite + plagioclase in core, marginal schistose hornblende + quartz + albite rock with almandine porphyroblasts	100-160
Metasediment and felsic metavolcanic	Feldspathic quartzite or recrystallized felsic tuffs/lavas with feldspar and quartz megacrysts (some eye-like), some amphibole, chlorite, biotite, garnet or iron-sulphide-bearing varieties	70-400
Perseverance ultramafic lens	Massive, medium- to coarse-grained, pale dunite-olivinite and dark grey serpentinized dunite-olivinite, granular and bladed textures; minor talc, magnesian carbonates, brucite, chlorite, tremolite, magnetite; anthophyllite porphyroblasts in dunite-olivinite; iron-nickel sulphides	20-650
Perseverance Fault breccia zone	Centred on vein quartz occupying the fault; sheared talc-carbonate and bladed-textured serpentinite inclusions of metasediment and amphibolite in the west; metasediment, chert (hornblende-pyrrhotite) and amphibolite in east	250-400
Un-named	Layered quartz-feldspar-biotite gneiss with amphibolite lenses	unknown
EAST		

Note: Modified from Allchurch (1974)

Dips remain steeply westwards as the geology is traced further north into the area of the Sir Samuel deposits. Here lenses of mineralized, foliated serpentinized dunite-olivinite occur in foliated talc-tremolite-chlorite rocks forming a unit up to 150 m thick which is contiguous with the mineralised unit at Leinster Downs prospect. Milne and Mason (1975) reported the presence of west-facing spinifex textures in talc-tremolite-chlorite rocks between the Sir Samuel and Leinster Downs deposits. Thinner, less continuous units of tremolite-chlorite schist are found in the metasedimentary schist interposed between the mineralised ultramafic and the Perseverance Fault at Leinster Downs and Sir Samuel. Recrystallized sulphidic chert and graphitic mica schist are more important components of the siliceous metasedimentary–metavolcanic country rocks in the north. The mineralized dunite-olivinite ultramafic units gradually diverge from the Perseverance Fault as they are traced northwards from Leinster Downs (200 to 300 m west of the fault) to north of Mount Sir Samuel (650 m west).

To the south of the Agnew deposit the Perseverance ultramafic lens again thins, but not as appreciably as in the north. Superficial deposits mask the geology, but auger drilling and magnetic surveys indicate the presence of discontinuous lenses of ultramafic rocks, in metasediments and more abundant mafic rocks, which occur in a 500-m-wide zone parallel to and immediately west of the Perseverance Fault.

MINERALIZATION

GENERAL

When production of development ore from the Agnew 1A shoot began in 1978, demonstrated reserves for the whole deposit were stated at 45 Mt averaging 2.05 per cent nickel (922 500 t contained nickel) and 0.10 per cent copper using a 1 per cent nickel cut-off. The Agnew deposit is therefore by far the largest single nickel sulphide deposit in the State, based on reserves averaging in excess of 1 per cent nickel. The deposit is comparable in the size of its reserves with the disclosed pre-mining reserve of the whole of the Kambalda group of deposits. In addition there are large tonnages of low grade mineralization containing less than 1 per cent nickel, which envelop, and extend immediately south of, the main deposit, and occur also at Melon and Eleven Mile Well deposits further south. The remaining deposits in the Agnew group are predominantly low grade and of small to moderate size, with the exception of the Sir Samuel deposits which contain an indicated resource of some 1.5 Mt averaging about 2 per cent nickel.

Disseminated sulphides in granular and bladed-textured serpentinized dunite-olivinite account for the bulk of the mineralization (85 per cent at Agnew deposit). The sulphides in bladed-textured rocks occupy triangular-shaped spaces between the network of randomly oriented, metamorphic olivine pseudomorphs which gives rise to 'triangular-textured ore'. Massive sulphides and more abundant breccia sulphides occur as lenticular, irregular bodies within and marginal to the disseminated sulphide shoots at Agnew and Sir Samuel; the most notable example is the 1A shoot which occupies a fault zone and extends some 600 m north from the ultramafic unit into the country rocks (Fig. 18). Physically oriented gangue and sulphide minerals may define a foliation in sulphide-rich ores, and coarse mineralogical layering is present in some thicker orebodies (e.g. 1A shoot). Pyrrhotite and pentlandite are the major primary sulphide minerals, which show the effects of strong deformation with little subsequent annealing by recrystallization. Pyrite is a minor phase and accessory chalcopyrite is present. Magnetite is most abundant, filling cracks in pentlandite; otherwise spinel phases are generally sparse. Millerite and heazlewoodite may occur in low grade mineralization. Valleriite-type minerals are finely disseminated in serpentinite, form thin veinlets, and may replace chromite phases.

Bulk Ni:Cu ratios are typically between 18 and 30, with the higher values generally coming from shoots rich in massive and breccia sulphide. This may reflect the preferential migration of copper during regional metamorphism.

AGNEW (PERSEVERANCE) DEPOSIT (27°48′55″S, 120°42′15–E)

General

Geological mapping in the region by Selco in 1970 showed that ultramafic rocks were common, and reconnaissance geochemical sampling outlined a weak anomaly near Perseverance Bore (Allchurch, 1974). More detailed mapping, systematic soil sampling, and ground magnetic surveys followed. The results of the soil sampling were discouraging, but the ground magnetic data indicated an abrupt widening of an ultramafic unit; it was decided to chip-sample previously mapped outcrops of silicified ultramafic rocks. Anomalous nickel and copper contents were found in some samples and subsequent mapping resulted in the discovery on 29 April 1971 of siliceous pseudogossan outcrops (Fig. 92B) near the contact of the ultramafic unit with steeply dipping metasedimentary rocks. This is the gossan developed on 1 shoot: samples assay 4 000 to 6 000 ppm nickel and 1 000 to 1 500 ppm copper and one contains a reported 222 ppb of palladium (Travis and others, 1976). Rotary percussion drilling of the gossan began on 17 May and nickel sulphides were intersected the following day. Diamond drilling began on 2 June 1971 and the first drillhole intersected massive nickel sulphides. The ensuing diamond drilling programme amounted to 216 drillholes (total 64 844 m) and was completed in December 1973. In early 1974 a winze was sunk to a depth of 118 m and crosscuts and drives made to provide bulk samples of the disseminated mineralization and massive sulphide. The drilling was used to demonstrate reserves of 45.2 Mt averaging 2.05 per cent nickel and 0.10 per cent copper at a 1 per cent nickel cut-off (Allchurch, 1974).

In June 1974, Mount Isa Mines Ltd acquired a 40 per cent interest in the Agnew nickel project, as a joint venturer with W. Selcast, and the Agnew Mining Company was formed to manage the project. In February 1976 it was decided to go ahead initially on the basis of a planned production of 10 000 t per annum of nickel in concentrates from a decline mine exploiting the massive ores of 1A shoot. Shaft sinking on the disseminated ore shoots was to be concurrent with the decline mining. In October 1976 agreement was reached with WMC for the toll smelting of concentrates at Kalgoorlie, beginning in 1979 when construction of a new flash furnace was completed. In July 1977 a ten-year contract for the sale of nickel matte was signed with Amax Nickel Inc; the matte was to be exported to Port Nickel, Louisiana for refining. The first matte shipment was made in December, 1978. The production of development ore from the 1A shoot began in early 1978, with the beginning of the first ore drive at 1 443 m RL (78 m below surface). Machine mining with jumbo drilling rigs is progressing from sill drives, initially spaced 35 m apart vertically from the 1 in 9 decline. The official start of mining was on 5 May 1978, the first full calendar year's production amounting to 58 693 t of concentrates averaging 10.79 per cent nickel. The shaft was completed to its planned depth of 910 m in 1980.

Structure

The general structure of the area has been described and the sequence of rock types present has been outlined previously (Table 16). The Perseverance and 60A Faults both appear to dip about 80 degrees westwards, that is, parallel to the attitude of the intervening sequence. Regional evidence suggests that this sequence occupies the overturned, eastern limb of an anticline (Martin and Allchurch, 1975).

The Perseverance ultramafic unit thickens abruptly to form a lens which is convex westwards, some 3 km long and up to 700 m thick (Fig. 18). The eastern contact of the lens is formed by the Perseverance Fault breccia zone, although some of the country-rock inclusions in the lens could be large xenoliths rather than being of tectonic origin. The western contact of the lens dips steeply westward but reversals occur where the mineralization is concentrated because of the presence of three ellipsoidal depressions occupying a steeply south-plunging trough in the contact (Martin and Allchurch, 1975). Numerous faults, generally dipping at 65 to 80 degrees westwards and striking between north and north-northwest, complicate the structure of the lens, particularly the western contact. Dip-slip movement of up to 300 m is indicated, although the prominent fault occupied by 1A shoot has a suggested dextral displacement of 130 m.

The Perseverance ultramafic lens

The Perseverance ultramafic lens consists of a large core of essentially unhydrated, granular-textured dunite-olivinite surrounded by serpentinized dunite with granular (igneous) and bladed (metamorphic) olivine pseudomorphs. An irregular transition zone of partly serpentinized dunite-olivinite, 10 to 100 m thick, is present between the dunitic core and serpentinite envelope.

The dunite-olivinite is grey and is composed of closely packed, subequant olivine crystals, which are up to 10 mm in diameter and are rarely pale brown in thin section, with rims, veinlets and small granulated aggregates of interstitial grains of colourless olivine. Accessory chromite may be present. Olivine is more rounded where interstitial sulphides are present. Both types of olivine are similar in composition, falling in the range Fo_{89} to Fo_{94} (Martin and Allchurch, 1975; Binns and Groves, 1976). There is debate on the origins of these two types of olivine: Martin and Allchurch (1975) and Hudson (pers. comm., 1979) favour an igneous origin for both, but Binns and Groves (1976) interpret the brown olivine as relict igneous, and the colourless olivine as metamorphic in origin. Much of the dunite-olivinite examined in this study contains porphyroblastic anthophyllite prisms up to 50 mm long and traces of talc, serpentine and chlorite, suggesting thorough thermal metamorphism with the presence of a little hydrous fluid. Fracturing of olivine grains is common and the fractures may be subparallel and define a crude foliation.

In the transition zone serpentinization proceeds via the fractures, leaving relict olivine cores and finally achieving complete hydration. Lizardite is the chief serpentine mineral. Talc and chlorite may increase in abundance and minor magnesite, brucite and tremolite may be present. Magnetite is conspicuous compared with its rarity in the dunite. The serpentinites are dark grey-green to black and either preserve the close-packed granular olivine texture of the dunite-olivinite or contain an interlocking, triangular network of bladed olivine pseudomorphs, up to 30 mm long, of probable metamorphic origin (Martin and Allchurch, 1975). Relict (metamorphic) olivine occurs in the cores of some blades of serpentine. Fine-grained serpentine, talc, chlorite, magnesite or sulphides may fill the spaces between the bladed pseudomorphs. The bladed-textured serpentinites seem to be better developed along the western margin of the ultramafic lens and in faulted zones. Either textural variant of the serpentinite may be foliated.

At contacts between the Perseverance ultramafic unit and country rocks or rare pegmatite intrusions, tremolite-, biotite-, chlorite- or talc-bearing selvedges are developed, which are interpreted as metasomatic reaction zones produced during regional metamorphism.

TABLE 17. CHEMICAL ANALYSES OF THE PERSEVERANCE ULTRAMAFIC LENS

Weight per cent	A	B
SiO_2	40.1	41.7
TiO_2	0.01	0.01
Al_2O_3	0.09	0.45
Cr_2O_3	0.20	0.16
Fe_2O_3	8.6	8.3
MnO	0.11	0.10
MgO	50.6	49.3
CaO	0.13	0.03
Na_2O	0.05	0.03
K_2O	0.01	0.01
P_2O_5	0.02	0.01

Notes:

1. Column A is average of 2 unserpentinized olivinites
2. Column B is average of 4 serpentinized olivinites and olivine-talc rocks
3. Total iron is expressed as ferric oxide
4. Analyses recalculated free of volatile components and nickel
5. Data are from University of Western Australia Geology Department

TABLE 18. DEMONSTRATED ORE RESERVES AND Ni:Cu RATIOS OF SHOOTS AT AGNEW DEPOSIT

Shoot	Disseminated ore (t)	Nickel Wt%	Copper Wt%	Massive ore	Nickel Wt%	Copper Wt%	Total contained nickel (t)
1	6 401 000	1.78	0.10	1 063 000	4.85	0.17	165 493
2	18 887 000	1.85	0.09	409 000	5.13	0.21	370 391
3	16 032 000	1.87	0.09	81 000	6.12	0.40	304 755
1A	163 000	1.39	0.08	1 544 000	4.63	0.19	71 487
Other	615 000	1.74	0.10	7 000	6.68	0.18	11 169
Total	42 098 000	1.84	0.09	3 104 000	4.81	0.19	923 295

Notes:

1. Figures based on cut-off grade of 1 per cent nickel
2. Data are from Allchurch (1974)

Some tremolitic serpentinites are developed near the eastern contact of the lens, but otherwise the Perseverance ultramafic lens is compositionally monotonous, averaging about 49 to 51 per cent magnesia (volatile-free) as indicated in Table 17.

Ore distribution and structure

The ore-grade (> 1 per cent nickel) portion of the deposit is concentrated at the western contact of the Perseverance ultramafic lens, where there is a pronounced inflexion in the contact (Fig. 18). This portion of the deposit is about 1 000 m long at the surface; subgrade mineralization extends southwards along the western contact for a further 1 000 m. The deposit is divided into four shoots: the 1, 2 and 3 shoots (numbered with increasing depth) consisting mainly of disseminated ore (average 15 to 20 per cent sulphides), and the 1A shoot consisting almost wholly of massive and breccia ore. Demonstrated reserves as indicated by the initial drilling programme are listed in Table 18. Mineralization is still open at depth. Some 84 per cent of the total reserve in terms of contained nickel is represented by disseminated ore, and more remains to be quantified below the deepest surface drillhole.

The four shoots overlap one another and, with the exception of the fault-controlled 1A shoot, seem to plunge steeply southwards in sympathy with embayments in the western contact fo the Perseverance ultramafic lens (fig. 19).An apparent reversal to a north plunge in 2 shoot at depth may be due to the extending along a fault, and the configuration of 1A shoot remains little known to the north below RL 1 100 m. The disseminated ore shoots probably have an irregular ellipsoidal shape and a maximum thickness of 80 m, but their complete geometry remains unknown. These shoots contain lower grade ore where their thickness decreases at a distance from the western contact. A zone of subgrade mineralized or barren ultramafic rock a few metres to a few tens-of-metres thick may be interposed between shoots and the western contact especially in the south (e.g. 2 shoot). Disseminated ore is confined to the serpentinite except for the eastern part of 3 shoot where sulphides occur in dunite-olivinite (Figs 94G, 95A). In both rock types, where granular-textured, the fine- to medium-grained varieties seem better mineralized than coarser grained varieties (D.R. Hudson, pers. comm., 1979). However in the bladed serpentinites there is no such relationship. Triangular-textured ores may be coarse- or fine-grained.

Massive and breccia ores are principally found as pinching and swelling, sheet-like bodies in faults cutting the western contact zone. The largest orebody is in the 'FS fault' which extends from the margin of 1 shoot northwards into the country rocks. That part of the massive ore outside the ultramafic lens is known as 1A shoot; this shoot is some 500 m long and has not been drilled out in depth (Fig. 19). The thickness of 1A shoot is very variable both along strike and vertically (Fig. 20); about 2 m would be an average thickness, but up to 12 m is attained locally where the fault is braided. Branches, veins and subordinate lenses of sulphides are typical. Thicker ore sections appear better developed at the south end of the shoot. Slivers of serpentinite and rosetted tremolitic ultramafic rock are found in and adjacent to 1A shoot up to several hundred metres north of the ultramafic lens (Fig. 20). Inclusions of these rock types, with the addition of vein quartz and country rocks, are of variable abundance within 1A shoot: breccia ore contains abundant inclusions; and massive ore consists of at least 80 per cent sulphides (Fig. 94F). The proportion of ultramafic inclusions increases southwards. Massive and breccia ore are foliated (oriented inclusions), and coarse mineralogical (pentlandite-pyrrhotite) layering develops in some massive ore; the layering typically 'flows' around large inclusions and follows irregularities in the margins of the shoot. The shoot margins are sharp and foliated, with no obvious post-tectonic effects of annealing by recrystallization.

Massive and breccia ores also occur within the disseminated ore shoots and at their contacts with country rocks. In the latter case the ores are similar to those described in 1A shoot, though inclusions of disseminated ores are also present. Sulphide-rich ores within the disseminated shoots contain inclusions of serpentinite and disseminated ore, and are generally not conspicuously foliated or layered. Thick (1 to 6 m) sheet-like orebodies seem to be restricted to faults, but locally there are numerous small patches, lenses and veins up to 25 cm thick of massive and breccia ore in serpentinite and dunite-olivinite (Fig. 94G), which apparently do not relate to cross-cutting strucutres. These small bodies tend to have gradational unfoliated margins with the enclosing disseminated ore and probably represent *in situ* developments in contrast to the fault-emplaced ores.

Ore petrology

Supergene alteration extends to a maximum depth of about 400 m, and has most effect on 1 and 1A shoots, but the top of 2 shoot is also altered. The amount of alteration is irregular and does not conform to a simple pattern. The deeper alteration is mainly related to fault zones. A detailed description of the petrology of supergene alteration is given by Nickel and others (1977). Shoot 1A crops out as a porous hematite gossan; two samples each assayed 320 ppm nickel, and 950 and 2 000 ppm copper. Oxidation is complete to a depth of about 50 m.

Nickel and others (1977) summarized the primary sulphide mineralogy as follows:

(i) massive (and breccia) sulphides—monoclinic pyrrhotite and pentlandite (in the ratio 4:1) with minor chalcopyrite and cobaltiferous pyrite. Magnetite and chromite are rare compared with volcanic peridotite-associated ores;

(ii) disseminated sulphides in serpentinite — hexagonal pyrrhotite and pentlandite, with minor chalcopyrite, pyrite and valleriite after chromite. Magnetite may be a major phase as veins in pentlandite;

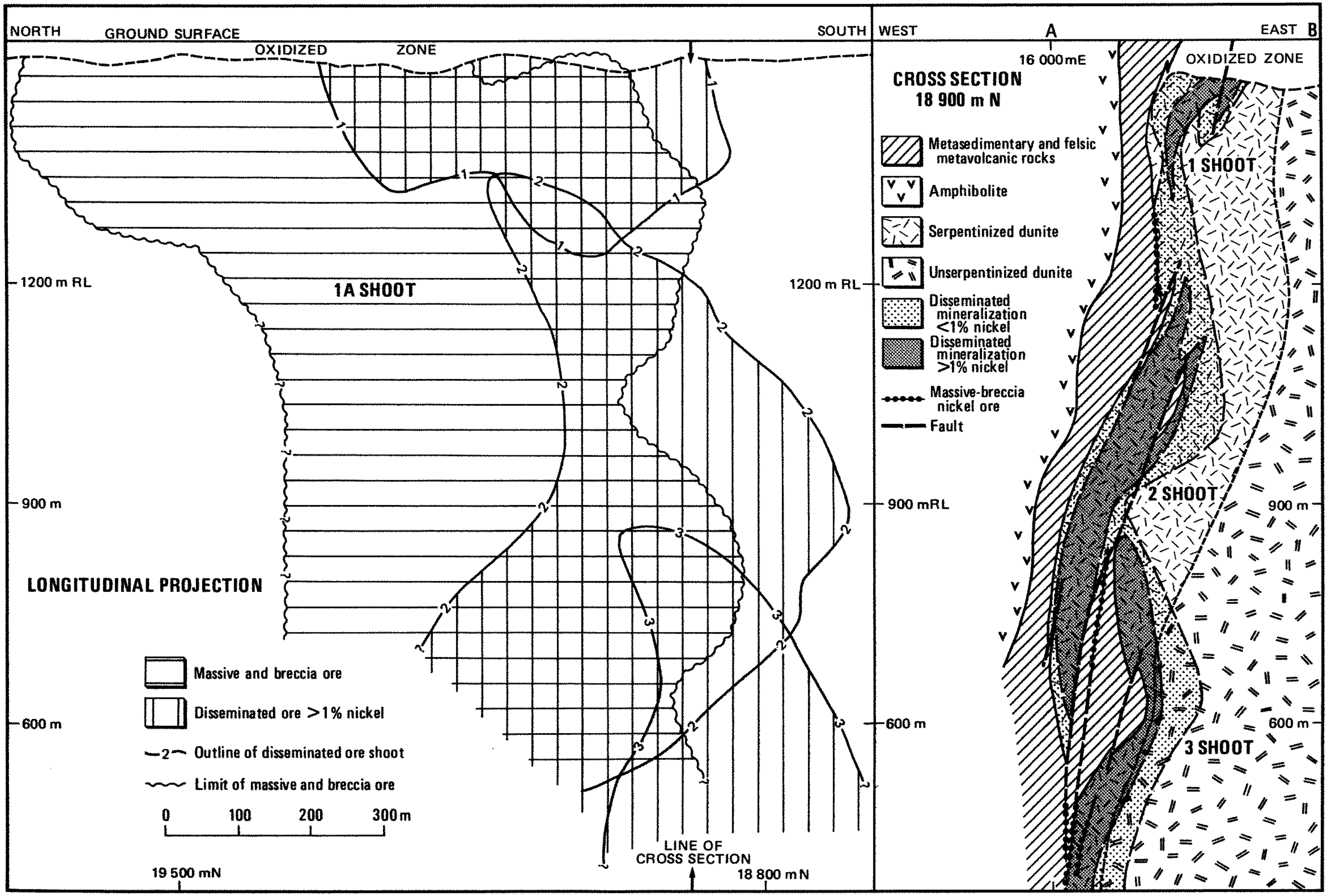


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Figure 19. Cross section and vertical longitudinal section projection through the Agnew deposit, based on Allchurch (1974).

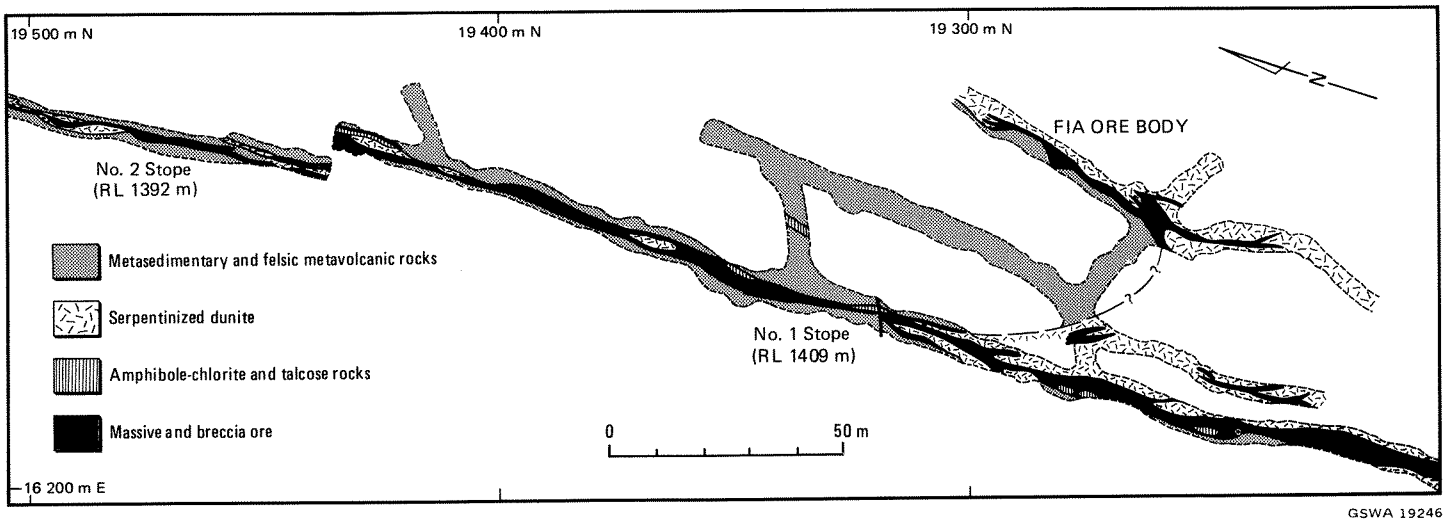

Figure 20. Geological plan of part of the number 1 and 2 stopes, 1A shoot, Agnew deposit.

(iii) disseminated sulphides in dunite-olivinite- pentlandite and pyrite with lesser monoclinic pyrrhotite and minor chalcopyrite, magnetite and chromite (some zoned);
(iv) disseminated subgrade (< 1% nickel) sulphides — pentlandite-pyrite-millerite or pentlandite-heazlewoodite.

Disseminated sulphides are fine to medium grained, whereas massive sulphides are more variable, ranging from fine to coarse grained, but the *in situ* massive sulphides are noticeably coarser grained than adjacent disseminated sulphides. Most sulphide in disseminated ore occurs as interstitial films and aggregates, but very fine-grained sulphides are dispersed throughout igneous or metamorphic olivine, or olivine pseudomorphs. The foliation defined by sets of cracks along which serpentinization took place, also traverses fractures, and brecciates pentlandite in disseminated ore. In the serpentinites, including partly serpentinized dunite-olivinite, the cracks in pentlandite are often filled by magnetite and rarely by pyrrhotite. In the unaltered dunite-olivinite, pyrite fills cracks in pentlandite. Pentlandite is less deformed in massive ore. Pyrrhotite forms irregular grains in massive ore and shows the effects of strong deformation without subsequent annealing: lanceolate deformation twinning and kink bands are abundant, and pyrrhotite-pyrrhotite grain boundaries are complex and sutured. Exsolved pentlandite flames are common, and fine-grained pentlandite may cluster along pyrrhotite grain boundaries. However, dimensional or optical orientation of pyrrhotite is uncommon. The lack of a late, static, annealing recrystallization of sulphides is reflected by the generally smooth, non-penetrative boundries between serpentine, talc and chlorite, and sulphides. In disseminated ore pyrrhotite is generally little deformed and forms more polygonal-shaped grains, but there are examples where it is deformed to the extent seen in massive ore. Triangular-textured ore seems to be characterized by more deformed pyrrhotite. Marginal break-up of the bladed metamorphic olivine pseudomorphs to produce gangue inclusions in the intervening sulphides is observed.

High-grade disseminated sulphides contain 1 to 3 per cent nickel, with a sharp drop in nickel and sulphide content to the subgrade mineralization. However, as indicated by the mineralogy the subgrade mineralization has a lower S:Ni ratio: Allchurch (1974) reported a mean of 1.9 compared with 3.6 for disseminated sulphides with more than 1 per cent nickel. The analyses of disseminated sulphides in Table 19 clearly show a decrease in the nickel content of the sulphide fraction with increasing sulphide volume. Massive sulphides have a still higher S:Ni ratio of about 5, which results in a mean nickel content of about 5 per cent with a range of from 4 to 8.5 per cent. This grade variation is determined by the amount of included gangue rather than variations in pyrrhotite:pentlandite ratio.

Unmineralized serpentinite or olivinite contains 2 500 to 3 000 ppm nickel whereas well-mineralized equivalents contain less than 1 000 ppm silicate nickel; this suggest that silicate nickel may have entered the sulphide phases (Allchurch, 1974).

ELEVEN MILE WELL AND MELON PROSPECTS (27°52′25″S, 120°45′10″E; 27°51′00″S, 120°44′30″E)

These prospects are 3.5 and 7 km respectively along strike to the south of the Agnew deposit in presumed equivalents of the Perservarance ultramafic unit. There is no outcrop. Both prospects seem to consist largely of subgrade disseminated sulphide mineralization in lenses of serpentinite and talcose serpentinite. Allchurch (1974) estimated that the economic potential of these deposits is low.

LEINSTER DOWNS PROSPECT (27°44′30″S, 120°40′10″E)

At Leinster Downs prospect, 8 km north-northwest of Agnew deposit, olivine-rich ultramafic rocks form a unit 50 to 150 m thick which occurs 200 to 300 m west of the Perseverance Fault (Fig. 17). The country rocks are similar to those at Agnew with a greater preponderance of magnetite- and pyrite-bearing quartzose rocks which have good induced-polarization and transient-electromagnetic responses. Exploration and was carried out by WMC from 1969 to 1975 (Donaldson, 1975). The olivine-rich ultramafic consists of medium- to coarse-grained serpentinized dunite-olivinite which exhibits pseudomorphs after either: (a) close-packed, granular, igneous olivine; or (b) after irregular, ovoid to bladed, metamorphic olivine. These textural types alternate or are transitional into one another. Type (b) textured rocks preferentially contain talc and carbonate minerals. Serpentine-amphibole-chlorite rocks are also present. Dips are steeply westwards.

Nickel assays in excess of 0.5 per cent were encountered in 21 percussion drillholes and 3 diamond drillholes bored by WMC. Deep weathering of the ultramafics indicates that most anomalous values in percussion drillholes were due to lateritic enrichment rather than nickel sulphides (Donaldson, 1975). Fine-grained disseminated pyrrhotite and pentlandite, with lesser pyrite, millerite, valleriite and magnetite are dispersed in small amounts throughout the serpentinite, but intersections assaying more than 0.6 per cent nickel over a minimum

TABLE 19. CHEMICAL ANALYSES OF THE SULPHIDE FRACTION OF DISSEMINATED SULPHIDES, AGNEW DEPOSIT

Weight per cent	1 A	1 B	2 A	2 B	3 A	3 B	4 A	4 B	5 A	5 B	6 A	6 B
Ni	4.37	11.56	1.89	9.69	2.09	13.75	1.21	18.62	0.97	31.39	0.27	44.00
Cu	0.19	0.50	0.04	0.18	0.10	0.69	0.02	0.26	0.01	0.06	0.01	0.67
Co	0.09	0.25	0.04	0.20	0.04	0.27	0.03	0.44	0.01	0.06	0.01	1.17
Fe	16.59	43.79	9.77	50.00	6.99	46.09	2.54	39.08	0.93	30.10	0.14	22.33
S	16.60	43.90	7.80	39.90	5.94	39.18	2.70	41.58	1.18	38.36	0.20	32.33
Total sulphides	37.8		19.5		15.2		6.5		3.1		0.6	
Ni:Cu	23		52		20		71		485		67	
Ni:Co	46		49		51		43		485		38	
S:Ni	3.8		4.1		2.8		2.2		1.2		0.7	
Fe:Ni	3.8		5.2		3.3		2.1		0.9		0.5	
Mineralogy	po-pn-py		po-pn		po-pn-py		pn-po		pn-py		pn-ml-py	

Notes:
1. Column B represents Column A recalculated to 100 per cent sulphides.
2. Mineralogy listed in order of decreasing abundance: po = pyrrhotite, pn = pentlandite py = pyrite, ml = millerite.
3. Samples 1,3,5 and 6 are from unserpentinized ultramafic rocks.
4. Sample 2 is from an ultramafic with 90 per cent serpentinization of olivine.
5. Sample 4 is from an ultramafic with 10 per cent serpentinization of olivine.
6. Data are from Binns and Groves (1976).

width of 2 m are rare. Some mineralization occurs in amphibole-chlorite rocks on the eastern side of the serpentinite. The best intersection was a drilled width of 1.8 m averaging 1.43 per cent nickel and 0.02 per cent copper. The mean Ni:Cu ratio of sulphide mineralization containing more than 0.5 per cent nickel is 26.

SIR SAMUEL DEPOSITS (approximately 27°42′10″S, 120°39′30″E)

The Sir Samuel deposits are 15 km north-northwest of the Agnew deposit, and some 500 to 700 m west of the Perseverance Fault. The geology is complex, outcrop is poor, and weathering is deep, especially over the ultramafic rocks. Most outcrop is made up of granular, recrystallized chert (some sulphidic) and weathered carbonaceous, siliceous and semi-pelitic schist.

Exploration by Kennco and subsequently Seltrust (Milne and Mason, 1975) in joint venture with ACM has identified lenses of mineralized, foliated and serpentinized dunite-olivinite (texturally like the Perseverance ultramafic lens) and more extensive foliated talc-tremolite-chlorite rocks forming a unit up to 150 m thick. This unit appears to be an extension northwards of the mineralized unit at Leinster Downs prospect, and in common with this prospect, thin tremolitic ultramafic units occur in the metasedimentary country rocks between the Perseverance Fault and the mineralized unit. Steep westerly dips prevail. Milne and Mason (1975) interpreted a series of gently north-plunging tight synclines and more open anticlines which have upright to steeply west-dipping axial surfaces. Strike faults occur in overturned fold limbs; the most persistent fault was called the Roman fault by Milne and Mason (1975). Northwest of Bailey Bore mineralized ultramafic rocks occur on both sides of the Roman fault which is located in the eastern limb of a syncline. the ultramafic unit east of the Roman fault lenses out northwards, whereas that to the west of the fault disappears southwards. One mineralized area (southern) occurs east of the fault, about 1 km northwest of Bailey Bore, and two areas (central and northern) are present west of the fault, 1 to 2 km north-northwest of the southern area.

In the northern area, diamond drilling (14 drillholes) by Kennco on traverse lines 122 m apart indicated that the ultramafic was weakly mineralized over a strike length of 1 100 m, and drilled average widths of 3 to 5 m with average nickel content of between 1 and 2 per cent. Seltrust undertook infill drilling (6 diamond drillholes) but this suggested that the disseminated sulphides were patchy along strike and down dip. The host rock is a foliated serpentinized dunite-olivinite with medium to coarse-grained, close-packed, igneous, olivine pseudomorphs, or bladed to lensoid metamorphic olivine pseudomorphs, accompanied by talc, carbonates, magnetite and chlorite.

In the central area Kennco partially tested fault slices of ultramafic with associated gossan after massive sulphides by drilling 1 diamond drillhole (DDH 25) and 9 percussion drillholes. Seltrust drilled 16 diamond drillholes spaced at intervals of 61 and 122 m along strike. Three drillholes sited in the south near DDH 25 intersected only weak mineralization. Thin (11 to 27 cm) intersections of massive nickel sulphides were encountered on the western, upper contact of the ultramafic 130 m (WKE 12), 250m and 400m north of DDH 25, but the best results were from 6 drillholes (WKE 18, 23-27) on two lines 65 m apart, situated some 500 m north of DDH 25 in a flat area devoid of outcrop. All of these drillholes cut thin (up to 1 m), west-dipping bodies, and veins of massive to breccia sulphides (pyrrhotite and pentlandite) assaying up to 5.5 per cent nickel, plus patchy developments of triangular-textured and fine-grained disseminated sulphides in serpentinite, like that in the northern area. Further drilling to the north indicated that this partly fault-controlled mineralized zone (from WKE 12 northwards) has a strike length of some 670 m.

In the southern area, one Kennco diamond drillhole (DDH 21) intersected two intervals of breccia sulphides assaying 3.72 per cent nickel over a drilled width of 1.64 m, and 2.56 per cent nickel over 0.76 m, associated with a thin fault slice of siliceous country rocks in foliated serpentinite. Infill drilling by Seltrust was unsuccessful in finding any significant extension to this mineralization. Only sparsely disseminated sulphides were encountered in the serpentinite.

Milne and Mason (1975) concluded that there was no likelihood of a commercially viable nickel sulphide deposit being present within 150 m of the surface in the Sir Samuel area.

YAKABINDIE GROUP

GEOLOGY

GENERAL

The nickel deposits of the Yakabindie group (David, Goliath, Mount Goode, Sheba, Six Mile Well) have a similar geological setting to the Agnew group, and are in a northward continuation of the same supracrustal belt (Fig. 17). In the Yakabindie area many strike faults converge as the belt narrows. Outcrop of most rocks except ultramafic varieties is fair to good.

Exploration has largely been undertaken by Anaconda-CRA, who have been active in the area since 1966. The largest deposit of the group, at Six Mile, was discovered in late 1970. Since mid-1976 WMC have conducted more detailed exploration in a joint venture with Anaconda-CRA, with most initial activity being in the Mount Goode prospect area. The most useful geological reports dealing with economic aspects are by Turner and Ranford (1975), Naldrett and Turner (1977) and Marjoribanks (1978). The regional geology is described by Bunting and Williams (1979). R.E.T. Hill is carrying out detailed petrological studies of the Six Mile deposit in particular. Regional metamorphism attained low amphibolite facies conditions (Barrett and others, 1977). Dynamic metamorphic textures are typical of metasedimentary and felsic metavolcanic rocks, whereas static to dynamic igneous textures prevail in many mafic to ultramafic rocks.

STRATIGRAPHY AND STRUCTURE

Despite the better outcrop, structural complexity does not allow an unequivocal stratigraphic succession to be erected (see discussion in Bunting and Williams, 1979). Olivine-rich ultramafic rocks occur in two areas: (i) adjacent to, and immediately east of, the Perseverance Fault (the Six Mile area); and (ii) south of Mount Goode, near faults which branch south-southwest from the Perseverance Fault. In both areas lenses of serpentinized dunite to olivinite are located in fine-grained clastic metasedimentary and felsic metavolcanic rocks similar to those described as country rocks for the Agnew group of deposits. The dunite-olivinite lenses of the Six Mile area are closely associated with spinifex-textured rocks of picritic to peridotitic composition which are found on both sides of the Perseverance Fault. The spatial association of dunite-olivinite lenses and major faults, and the indication that some lenses may transect folds, led Turner and Ranford (1975), and others, to interpret the lenses as late- to post-tectonic intrusions, unrelated to the earlier ultramafic volcanics. Naldrett and

Turner (1977) presented an important change in interpretation which envisages the lenses as stratigraphically controlled intrusions representing the sub-volcanic phases of the associated extrusive ultramafic rocks. Marjoribanks (1978) agreed with their interpretation, and further suggested that the Six Mile area lenses could represent the boudinaged remnants of a single tabular intrusion.

According to Naldrett and Turner (1977), the Six Mile area lenses are situated in the eastern limb of a syncline which parallels the Perseverance Fault; to the south the fault occupies the axial zone of this syncline. To the west is a complementary anticline (cored by metabasalt) which can be traced south to McDonough Lookout (Fig. 17). Further west is a complexly faulted synclinal zone occupied mainly by conglomeratic metasediments in which the Mount Goode ultramafic lenses are located. Felsic metavolcanic rocks and fine-grained semi-pelitic metasediments form some of the country rock at Mount Goode but lack of exposure prevents their relationship to the conglomeratic rocks from being determined. The stratigraphy of the Six Mile area is summarized in Table 20. Dips are moderate to steep and generally westerly.

TABLE 20. STRATIGRAPHY OF THE SIX MILE AREA

Unit	Lithology	Approx thickness (m)
Jones Creek Conglomerate	Granitoid conglomerate, arkose, mafic conglomerate, ultramafic paraschist	unknown
---------- *Unconformity* (tectonized) ----------		
Serp Hill metaperidoitite	Serpentinized olivine peridotite with cumulus texture, conformable	100 m
(Cherty metasediment marker horizon)		few metres
Layered series	Basaltic to ultramafic flows and intrusive rocks; interlayered metabasalt and metagabbro to pyroxenite prominent in upper part; magnesian metabasalt and spinifex-textured ultramafic flows prominent in lower part	600-800 m
(Cherty metasediment marker horizon)		few metres
Dunitic lenses	Serpentinized black dunite-olivinite grading outwards into dark green-grey olivine peridotite; emplaced into top of volcanogenic sediment unit; disseminated nickel sulphides in some lenses	300-500 m
Volcanogenic metasediment	Quartz, actinolite, garnet, biotite, chlorite and andesine-bearing rocks; poorly bedded; some of pyroclastic origin; some cherty and slaty horizons	500-700 m
(Cherty metasediment marker horizon)		few metres
Metabasalt	Tholeiitic metabasalt with some lenses of magnesian metabasalt near the top	>500 m

After Naldrett and Turner (1977) and Marjoribanks (1978)

MINERALIZATION

GENERAL

The mineralized olivine-rich ultramafic lenses are near-vertical, conformable, symmetrical bodies consisting of a core of dunite-olivinite, now largely converted to a black lizardite-antigorite serpentinite, enclosed in an envelope of dark-green to black, seprentinized, olivine peridotite (Turner and Ranford, 1975). Some fresh olivine occurs in the core rocks. The olivine pseudomorphs are medium to coarse grained and polygonal and closely packed in barren dunite-olivinite, but tend to be more rounded and lobate where interstitial sulphides are present (R.E.T. Hill, pers. comm., 1979). Talc-magnesite alteration is patchily developed in the core or envelope rocks, and commonly takes the form of reticulated veinlets along which nickel sulphides may also be localized, especially in places where the serpentinized olivine peridotite is mineralized (Naldrett and Turner, 1977).

In the Six Mile area, faults truncate several lenses on the eastern side, so that the eastern peridotitic margin is poorly represented, or absent. An exception seems to be the Sheba prospect lens which preserves an eastern peridotitic margin, and also contains a thin vein of massive nickel sulphides on the sheared eastern contact between serpentinized peridotite and metasediment. This is the only known occurrence of massive sulphide in the Yakabindie group.

The bulk of the mineralization consists of uniformly distributed interstitial sulphides which average 0.6 per cent nickel and 0.01 per cent copper, using a cut-off figure of 0.4 per cent nickel. Pentlandite (or violarite) and pyrrhotite are the chief sulphide phases. Although the tonnages are large (probably at least 80 Mt at the tenor stated), the deposits are not commercial under present market conditions with conventional mining techniques.

SIX MILE DEPOSIT (27°25′20″S, 120°34′10″E)

Six Mile deposit, the largest deposit in the Yakabindie group, is located at the northern end of the group, 7 km south-southeast of Mount Falconer (Fig. 17). Naldrett and Turner (1977) described the petrology of the olivine-rich ultramafics and the mineralization in some detail, and the following account is largely based on this work and Turner and Ranford (1975).

The deposit was discovered by Anaconda geologists in August 1970, when diamond drilling, sited to test geological targets with associated induced polarization anomalies (which proved to coincide with sulphidic black slate), encountered disseminated nickel sulphides in serpentinite. A sample of weathered mineralized serpentinite from the surface analyzed by Travis and others (1976) contained 900 ppm nickel, 190 ppm copper, 21 ppb palladium and 8 ppb iridium. Diamond drillholes were put in on traverses spaced 244 m apart along strike, over a strike length of about 1 500 m. Indicated resources are at least 60 Mt averaging 0.6 per cent nickel and 0.01 per cent copper at a cut-off of 0.4 per cent nickel.

The serpentinized dunite-olivinite core of the Six Mile lens is some 1 400 m long (north-south) and 200 m wide at the surface. Including the peridotitic envelope, the whole lens is up to 400 m wide, and the peridotitic rocks (with nickel mineralization) continue northwards beyond the northern boundary of Anaconda-CRA tenements, into a block of Metals Ex tenements. Massive, green, serpentinized peridotite crops out in the southwestern corner of the lens, but the remainder of the lens is covered by a siliceous lateritic weathering profile which thickens northwards. The lens is vertical to steeply west-dipping, and has been drilled to a vertical depth of 600 m in the south, but drillholes in the north passed below the central dunitic core, indicating a southerly plunge. The eastern contact is partly intrusive and partly faulted, whereas the western contact is comfortable with overlying west-dipping metasediments (especially the cherty marker horizon). Minor folds in these metasediments plunge at 25 degrees towards the south-southwest, and are seen to advantage immediately west of Six Mile Well.

The serpentinized olivine peridotite (35 to 45 per cent magnesia, volatile-free) envelope contains lizardite or antigorite, plus minor brucite, tremolite, talc, magnesite and chromite. A narrow zone of mineralization up to 850 m long and 25 m wide is present in the western part of the envelope; pentalandite + pyrrhotite (∓ niccolite, maucherite, cobaltite and pyrite) occurs mainly in carbonate veinlets forming networks in the peridotite in the south, whereas ragged blebs of pentlandite and pyrrhotite characterize the peridotite to the north. The dunite-olivinite (45 to 51 per cent magnesia) core which is host to the bulk of the mineralization, is mainly completely serpentinized to lizardite or antigorite but areas of relict olivine (Fo_{95}) remain (e.g. drillhole SMD 320D). Zoned chromite grains with magnetite rims are an accessory phase. Networks of carbonate veinlets are locally present. Pentlandite and pyrrhotite plus minor pyrite and chalcopyrite occur interstitially to the olivine pseudomorphs in a zone 50 to 100 m wide running the full length of the dunitic core, and beyond into peridotitic rocks to the north. The mineralization in the dunitic core tends to be of slightly lower tenor than that in the peridotitic envelope. Much of the dunitic core is characterized by subparallel sets of cracks which traverse olivine, serpentine and pentlandite in similar fashion to microfractures in the Perseverance ultramafic. Carbonated olivine-rich ultramafics may be foliated or even schistose, otherwise there is no obvious deformation texture in the lens besides the fracturing mentioned.

Where disseminated sulphides are very low in abundance, the nickel-rich phases millerite, heazlewoodite and godlevskite may be present. Naldrett and Turner (1977) interpreted the presence of these minerals as a product of the local migration of silicate nickel, derived from olivine during serpentinization, into the available sulphide phases. Turner and Ranford (1975) pointed out that the serpentinite gangue has an abnormally low nickel content (about 0.12 per cent) compared with the expected value for such a magnesian rock (*cf.* Fig. 7). Naldrett and Turner (1977) suggested that the original silicate content of the dunite-olivinite was about 0.37 per cent nickel.

Supergene alteration has occurred to a depth of some 150 m, and the oxidized zone is 30 to 70 m thick.

GOLIATH NORTH DEPOSIT (27°27′10″S, 120°35′10″E)

This deposit is 3 km south-southeast of Six Mile deposit, and is contained in a similar, but smaller lens of black serpentinized dunite-olivinite mantled by serpentinized olivine peridotite (Naldrett and Turner, 1977). The lens forms a ridge capped with brown, silicified, weathered rock in which the medium- to coarse-grained, close-packed, olivine-pseudomorph texture is still preserved. Some small serpentinite outcrops occur at the base of the ridge on the western side. The surrounding country rocks are foliated, lineated and schistose. A recrystallized chert on the western contact of the lens dips northwest at 50 to 80 degrees. The eastern contact dips at 80 degrees eastwards. At the surface the lens is 1 000 m long and 200 m wide, and it tapers northwards.

The lens was first drilled by Anaconda-CRA in August, 1971. Four diamond drillholes on three traverses spaced 244 m apart along strike, intersected black serpentinite containing low-grade disseminated iron-nickel sulphide mineralization like that at Six Mile deposit. The mineralization appears to be continuous over a strike length of 488 m and is open to the north, to the south, and at depth. In this strike length there is an indicated resource of 20.45 Mt averaging 0.62 per cent nickel at a cut-off of 0.40 per cent nickel. Only two diamond drillholes penetrated the eastern (presumed basal) contact of the lens.

SHEBA PROSPECT (27°28′10″S, 120°35′25″E)

Sheba prospect is 7 km south-southeast of Six Mile deposit, and is immediately east of the Perseverance Fault. The ultramafic lens strikes slightly west of north, is 1 600 m long and up to 150 m wide, and consists of serpentinized green peridotite to dunite. Outcrop is very poor; laterite rubble covers most of the lens, but as a follow-up to geochemical drilling in 1977, lateritized and silicified ironstone outcrops were found by Anaconda-CRA on the eastern contact in the north (Kavanagh, 1979a). A diamond drillhole (SPD 136A) sunk in November 1977 to test a copper-nickel-cobalt anomaly coinciding with these outcrops, intersected a drilled width of 1.43 m averaging 4.32 per cent nickel and 0.34 per cent copper. This width included a 61-cm-thick vein of massive sulphides (violarite, pyrrhotite, pyrite, chalcopyrite) containing fragments of chloritic serpentinite. The mineralization occurs at a contact between foliated felsic (tuffaceous?) rocks and strongly foliated pale serpentinized olivine peridotite with chloritic and talcose varieties. These ultramafic rocks are in the eastern peridotitic envelope to a dunitic core.

Two diamond drillholes sited to the north and south of the discovery drillhole, failed to intersect any mineralization, and a fourth drillhole sited to test another of the ironstone outcrops was also barren. Further geochemical drilling was carried out in 1978, but follow-up drilling was again without success.

MOUNT GOODE PROSPECT (27°36′25″S, 120°34′15″E)

Mount Goode prospect is 4 km south of Mount Goode and 3 km northeast of the abandoned Sir Samuel townsite. The prospect is at the northern end of a north-striking, largely concealed unit of serpentinized peridotite to dunite and serpentine-amphibole-chlorite rocks, which appears to be more or less continuous for 7 km northwards from Lake Miranda. The country rocks are mainly fine-grained semi-pelitic metasediments of felsic volcaniclastic affinity which are intruded by metadolerite and granitoid rocks, but all these rocks are poorly exposed also. The contact relationships of the ultramafic unit suggest that it has intruded the country rocks.

Exploration by Anaconda-CRA defined a serpentinized peridotite-dunite lens about 1 500 m long and up to 400 m wide, with a steep to vertical dip. Relict igneous olivines occur in the core of the lens, which is dunitic in composition, and pyroxenitic to peridotitic rocks tend to occur marginally. Patchy talc-carbonate alteration has affected some ultramafic rocks. Three diamond drillholes encountered low-grade disseminated nickel sulphide mineralization in or near the eastern contact of the lens. Average nickel contents are generally 0.5 to 0.8 per cent, the best intersection being a drilled width of 6 m of dark-grey to green serpentinized olivine peridotite, which averaged 1.8 per cent nickel (MGD 106A). Three other diamond drillholes were barren of mineralization.

Since July 1976, WMC have conducted more detailed exploration including further ground magnetic surveys, geochemical drilling, transient electromagnetic surveys and contact drilling by rotary-percussion drills. Several geochemical anomalies proved to be the result of enhancement of nickel contents in lateritic weathering profiles developed over the ultramafic lens.

MOUNT KEITH GROUP

GEOLOGY

GENERAL

The nickel deposits of the Mount Keith group (Betheno, Honeymoon Well, Kingston, Mount Keith, Mount Keith – Cliffs/Charterhall) have a geological setting which is similar to that of the Six Mile area deposits described above. The supracrustal belt extending northwards from Six Mile gradually reaches a width of 10 km north of Mount Keith, and then remains constant as far as the Honeymoon Well prospects at the northern end of the group of deposits (Fig. 17; Plate 1). Outcrop is poor; amphibolite on the eastern margin of the belt forms the only good outcrop. Ultramafic rocks are rarely seen at the surface, except in an oxidized and lateritized condition. Alluvium and colluvium are extensive.

Exploration between Betheno and Kingston has been carried out mainly by Metals Ex and joint venture partners since 1969. Other companies who have been actively involved include CRA (at Honeymoon Well) and Cliffs-Charterhall (at Mount Keith – Cliffs/Charterhall). Besides the work of the two last-mentioned companies, there has been little activity since 1972 at Mount Keith, or since 1977 at Honeymoon Well. The geology and mineralization of the Mount Keith deposit are described by Burt and Sheppy (1975), and Butt and Sheppy (1975) discussed problems in geochemical exploration at the same deposit. More specialized studies on the metamorphic aspects of the olivine-rich ultramafic rocks and their contained mineralization are those by Groves and Keays (1979) and Donaldson (1980). The regional geology is described by Bunting and Williams (1979) and Elias and Bunting (1978). D.R. Hudson and R.E.T. Hill are carrying out detailed petrological studies of the Mount Keith deposit.

Metamorphic assemblages in the olivine-rich ultramafic and other country rocks indicate that the regional metamorphic grade attained declined from lowermost amphibolite facies conditions in the south to mid-greenschist facies in the north (Barrett and others, 1977). Dynamic metamorphic textures are typical of metasedimentary, felsic metavolcanic and some metabasaltic and ultramafic rocks, but olivine-rich ultramafic rocks are typified by static igneous textures with a weak foliation developed locally.

STRATIGRAPHY AND STRUCTURE

The Perseverance Fault continues northwards from the Six Mile area and can be traced throughout the strike length of the Mount Keith group where it consistently forms a boundary between the Joes Creek Conglomerate to the west, and olivine-rich ultramafics, metavolcanics and metasediments to the east (Fig. 17). Neither Burt and Sheppy (1975) nor Butt and Sheppy (1975) recognized this fault and both papers imply that the supracrustal rocks form a single succession which faces eastwards. Dips are vertical or steeply westwards. The structure and stratigraphy of the Six Mile area (see above) indicates that the eastern limb of a syncline is preserved and truncated to the west by the Perseverance Fault. For the Wiluna region, Elias and Bunting (1978) suggested, from limited facing observations and an apparent ultramafic-mafic to felsic metavolcanic sequence from east to west, that the regional structure of the supracrustal belt east of the Perseverance Fault corresponds to the eastern limb of a north-northwest-trending syncline. This appears to be complicated at Honeymoon Well by the presence of eastfacing ultramafic flows. Whilst admitting that internal faulting and folding is likely within the belt east of the fault, it is considered that, from available evidence, the faulted synclinal interpretation is feasible for the Mount Keith group.

The olivine-rich ultramafic rocks form an essentially single series of lenses for 18 km of strike from Betheno to Mount Keith: the thickest lenses occur at Betheno (550 m) and Mount Keith (650 m). At Mount Keith a subordinate lens occurs west of a sulphidic metasediment marker horizon, whereas the main series of lenses is slightly oblique to the strike and crosses to the east of this horizon to continue north-northwestwards to Kingston. Here there are at least two zones of olivine-rich ultramafics, which join and branch in a complex manner, partly for tectonic reasons. The two zones evidently continue northwards to merge at Honeymoon Well and branch again to the north. A black sulphidic slate occurs on the western contact of the olivine-rich ultramafic at Honeymoon Well.

Throughout the Mount Keith group there is a general spatial association of olivine-rich ultramafic lenses with spinifex-textured ultramafic flows and metabasalts, which are found interspersed with other country rocks to the west of the lenses. Therefore, these mafic to ultramafic volcanic rocks may be broadly equivalent to the 'layered series' in the Six Mile area (Table 20). Accordingly, though intrusive and locally transgressive, the lenses may be at least partly stratigraphically controlled.

MINERALIZATION

GENERAL

The mineralized lenses are near-vertical or steeply west-dipping, semi-conformable bodies consisting of green-grey or black, serpentinized dunite-olivinite which may have marginal zones of green, serpentinized peridotite to olivine peridotite. Partly serpentinized olivinite occurs in the core of the Betheno lens, and meta-pyroxenite is present marginal to some olivine-rich ultramafics at Kingston. The olivine pseudomorphs are medium to coarse grained, polygonal and closely packed, but tend to be more rounded where interstitial sulphides are present. Irregular zones of talc-carbonate alteration affect the serpentinites; the more intensely altered zones are generally foliated and lack any inherited igneous texture. Early stages of alteration may involve the development of reticulated carbonate veinlets.

The sulphide mineralization consists mainly of uniformly distributed low-grade disseminated sulphides which rarely contain more than 1 per cent nickel on average. The mineralization may be dispersed through the bulk of the lens or be concentrated in one or more lenticular zones, some of which may be marginal. The bulk of this type of mineralization is in the Mount Keith deposit which contains a demonstrated resource of 263 Mt averaging 0.6 per cent nickel and 0.01 per cent copper at a cut-off of 0.4 per cent nickel. Resources at Honeymoon Well are much smaller but of higher grade, averaging 1.1 per cent nickel. Kingston and Betheno mineralization is usually lower grade than Mount Keith. Pentlandite (or violarite), pyrrhotite and heazlewoodite are the chief sulphide phases. Spinel phases are altered to distinctive purple stichtite in many serpentinites. Nickel arsenides are present in some talc-carbonate rocks.

Before the recent discovery by Cliffs-Charterhall south of Mount Keith, massive nickel sulphides seemed to be a very rare feature of the mineralization; isolated, small intersections had been found only at Honeymoon Well. The host ultramafic unit at Mount Keith - Cliffs/ Charterhall partners prospect appears to be a monotonous talc-carbonated rock immediately west of the Mount Keith-Betheno series of serpentinite lenses. The presence of a laminated sulphidic metasediment on the mineralized contact appears to be more than coincidental as the massive to breccia sulphides are iron-rich, with an average nickel content of 2 to 3 per cent.

MOUNT KEITH DEPOSIT (27°14′50″S, 120°32′30″E)

General

The Mount Keith deposit, the largest so far known in the Mount Keith group, is located 7 km south of Mount Keith trigonometrical point, 300 to 600 m east of the old Leonora-Wiluna road. Exploration in the area by Metals Ex in a joint venture with Freeport began in January 1969, following the discovery of nickel sulphides by local pastoralist J.T. Jones who drilled a weathered ultramafic outcrop in November 1968. Magnetic and induced polarization surveys and extensive shallow rotary drilling (710 drillholes totalling 26 364 m) to obtain geological and geochemical data were undertaken by Metals Ex, as managers, in the first half of 1969. Systematic diamond drilling on the resulting targets began mid-year, and in November 1969 drillhole MKD 5 intersected disseminated nickel sulphides in a serpentinite lens concealed by alluvium. In June 1972, after 32 inclined diamond drillholes (total 14 133 m) had been sunk, a demonstrated resource of 263 Mt averaging 0.60 per cent nickel, 0.01 per cent copper, and about 0.02 per cent cobalt was calculated using a cut-off of 0.40 per cent nickel. This figure is based on mineralization that would be available in an open pit 2 300 m long, up to 1 300 m wide and a maximum of 600 m deep. The deposit is open at depth.

A vertical winze was sunk to 153 m depth to provide bulk samples for metallurgical testwork. This winze was sunk through 26 m of transported superficial deposits, followed by 36 m of ferruginous and siliceous lateritic profile, before supergene sulphides were encountered at a depth of 62 m (Butt and Sheppy, 1975). Primary sulphide mineralization occurred below a depth of 89 m. Iron-rich and siliceous pisolitic material at the top of the weathered profile over the mineralized serpentinite had mean nickel contents in the range 815 to 2 020 ppm, and copper 150 to 500 ppm (Butt and Sheppy, 1975). However, more typical nickel contents from the weathered zone at 30 m depth are in excess of 4 000 ppm.

The present title to the tenements is held one half by Freeport Minerals and one half by Mt Keith ACM Pty Ltd (Mt Keith ACM Pty Ltd is owned by Amax, two thirds, and ACM, one third). Exploration activity by this group resumed in 1981 following a long period of dormancy.

The host ultramafic unit

The general structure and stratigraphy of the area has been described above and is illustrated in more detail in Figure 21. Olivine-rich ultramafic rocks form a particularly thick (up to 650 m) lens at the deposit, which generally dips westwards at about 80 degrees. Although the lens is commonly conformable with the dip of the country rocks, it is clearly transgressive, as seen, for example, immediately southwest of the winze where a laminated sulphidic metasediment is truncated abruptly by ultramafic rocks.

The lens is dominated by medium- to coarse-grained, grey-green serpentinized olivinite which may preserve textures pseudomorphic after close-packed polygonal olivine. This texture commonly remains in grey to black, serpentinized olivinite which forms the core of the lens, although in detail black and green serpentinites may alternate with one another. The serpentine is largely 'hour-glass' textured lizardite with recrystallization to antigorite along grain boundaries and fractures. Veinlets of chrysotile are locally present. Both types of serpentinite are affected by zones of talc-magnesite alteration of varying intensity, manifested by talc-carbonate veinlets and bleaching of the serpentinite. The serpentinites are normally little deformed, whereas talc-magnesite rocks are commonly foliated. On a volatile-free basis the bulk composition of the rock suffers little change: an average composition is given in Table 21, column B. Serpentinized peridotite and orthopyroxenite form a thin margin to the lens on its western side (Burt and Sheppy, 1975, Fig. 3). Magnetite is an abundant accessory in most rocks, accompanied by lesser chromite rimmed by magnetite, pink stichtite after chromite, valleriite after chromite, and magnetite.

TABLE 21. CHEMICAL ANALYSES OF METAMORPHOSED OLIVINE-RICH ULTRAMAFIC ROCKS AT BETHENO AND MOUNT KEITH

Weight per cent volatile-free	A	B
SiO_2	40.9	42.5
TiO_2	0.01	0.02
Al_2O_3	0.12	0.34
Cr_2O_3	0.23	0.28
Fe_2O_3	7.1	7.5
MnO	0.13	0.08
MgO	51.5	49.1
CaO	0.09	0.17
Na_2O	<0.01	<0.01
K_2O	0.01	0.02
P_2O_5	0.01	0.01

Notes:

1. Column A is average of 3 slightly serpentinized olivinites from Betheno
2. Column B is average of 9 serpentinized olivinites and talc-magnesite rocks from Mount Keith
3. Total iron is expressed as ferric oxide
4. Analyses recalculated free of volatile components and nickel
5. Data are from University of Western Australia

Thin, undeformed but metamorphosed intrusions of dolerite and gabbro cut the western portion of the lens.

Sulphide distribution and petrology

Mineralization of potential commercial importance occurs continuously over a strike length of some 1 850 m, with an average width of 180 m and a maximum width of 320 m (Burt and Sheppy, 1975). In the widest part of the deposit, centred on the winze, disseminated sulphide mineralization averaging more than 0.4 per cent nickel occupies about three-quarters of the full width of the ultramafic lens, is centrally disposed (Fig. 21), and persists to a depth of at least 500 m. Thus black serpentinite contains the bulk of the mineralization. Supergene violarite, pyrite and marcasite occur to a depth of 80 to 90 m in most places.

The common primary assemblage of the opaque phases is pentlandite-pyrrhotite-magnetite plus, in some samples, accessory chromite, pyrite and chalcopyrite. In rocks more affected by talc-carbonate alteration millerite, gersdorffite, heazlewoodite, polydymite, awaruite and bravoite may be present (Burt and Sheppy, 1975; Groves and Keays, 1979). Sulphide-oxide aggregates, up to a few millimetres in diameter occur along the boundaries of olivine pseudomorphs, the larger aggregates being at the junction of several pseudomorphs. In black serpentinite which is undeformed and lacks any talc-carbonate alteration, the opaque mineral aggregates are lobate with minor marginal recrystallization involving gangue minerals. With increasing carbonate veining and antigorite growth, the opaque mineral aggregates are increasingly recrystallized both internally and with respect to marginal gangue phases

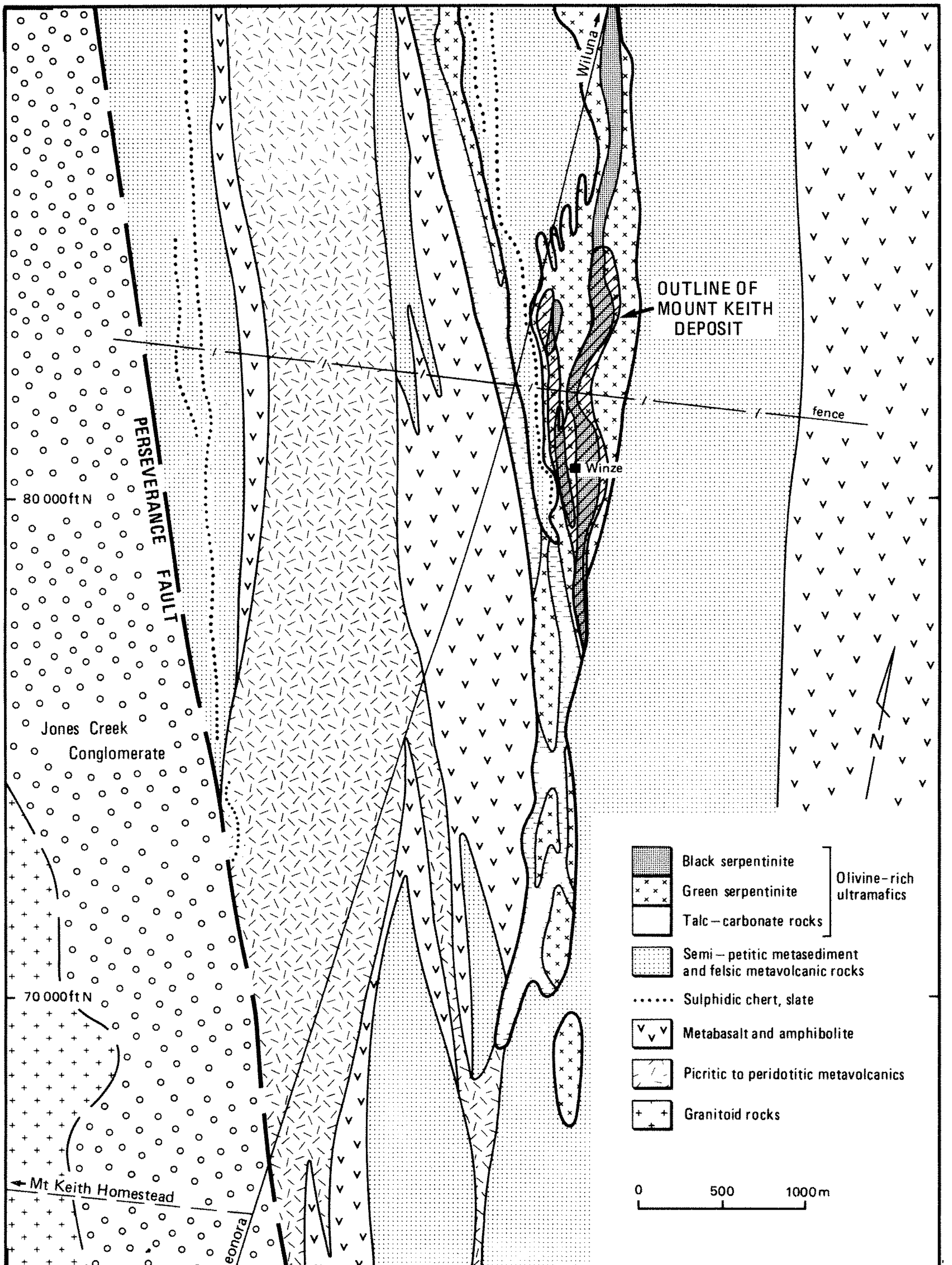

Figure 21. Geological map (interpreted subcrop) of the Mount Keith deposit, based on Burt and Sheppy (1975).

(Groves and Keays, 1979). Pentlandite is typically coarsely fractured and veined by magnetite and gangue phases (especially magnesite) pyrrhotite is rarely veined by magnetite, but both sulphide minerals (as an aggregate) are rimmed by magnetite. Pyrrhotite shows little evidence of internal strain besides a few kink bands in some grains. In addition to the aggregates between olivine pseudomorphs, very fine-grained sulphide and oxide grains are found within the pseudomorphs, particularly in serpentinites traversed by carbonate or antigorite veinlets and in talc-magnetite rocks.

Sulphide contents rarely exceed 5 per cent of the rock volume. Nickel tenor ranges from 0.4 to 0.8 per cent, with about 0.1 per cent of this being represented by non-sulphide nickel (Butt and Sheppy, 1975) Exceptionally, nickel tenors up to 2 per cent are present, apparently where sulphides have been concentrated in abundant carbonate veinlets (Butt and Sheppy, 1975).

More sulphidic nickel sulphides have not been found, although the pattern of diamond drilling employed (drillholes collared in the west and inclined eastwards) means that the eastern contact has been inadequately tested. In this context, two items are of possible relevance. Firstly, the discovery of extensive massive sulphides on the eastern contact of an olivine-rich ultramafic at Mount Keith - Cliffs/Charterhall partners prospect (see later), and secondly the presence of a strong bedrock geochemical anomaly on the eastern contact of the Mount Keith lens, some 5.5 km north of the winze (Burt and Sheppy, 1975). This anomaly, containing up to 1.5 per cent nickel and 1 100 ppm copper persisted from a depth of 10 m to nearly 100 m, but a diamond drillhole encountered only disseminated pyrrhotite (in the primary zone) in serpentinite which assayed up to 0.29 per cent nickel.

The eastern contact of the lens warrants more thorough testing for the possible presence of massive nickel sulphides. The apparent restriction of less magnesian ultramafic rocks to the western margin of the lens suggests that the eastern margin could be the stratigraphic base, and therefore have important economic potential.

BETHENO PROSPECT

Betheno prospect is 18 km south of Mount Keith deposit, and 3 km north of Six Mile deposit to which it is closely similar. Exploration, including diamond drilling, has been carried out by Metals Ex. The prospect occurs in a lens, some 1 700 m long and up to 550 m wide, which consists mainly of black, serpentinized olivinite with a core of little-hydrated, medium- to coarse-grained olivinite (Table 21, column A) and some marginal talc-magnesite rock (Groves and Keays, 1979). The country rocks are mainly metasedimentary and felsic metavolcanic rocks. Disseminated sulphides occur in all the ultramafic rock types. Outcrop is moderate, though generally weathered. Lobate pentlandite is the only opaque phase besides chromite in the fresh olivinite, and is present in amounts from 0.5 to 6 weight per cent (Groves and Keays, 1979). Heazlewoodite and magnetite progressively replace pentlandite in partly serpentinized olivinite, and then more iron-rich assemblages, similar to those at Mount Keith, occur in the serpentinites and talc-magnesite rocks. Groves and Keays (1979) interpreted these changes in terms of element redistribution during progressive metamorphic alteration.

Compared with Mount Keith, mineralization at Betheno is lower grade, more patchy, and has a shorter strike length. The more continuous and thicker mineralized intersections are mainly restricted to the olivinite core and its partly serpentinized margins.

KINGSTON PROSPECT(26°58′20″S, 120°04′30″E)

This prospect is 32 km along strike to the north-northwest of the Mount Keith deposit (Plate 1) and 6.5 km west-southwest of Lake Way homestead. Outcrop at the prospect is poor; most ultramafic rocks are concealed.

Tenements were first pegged by local pastoralists in 1968 to cover an aeromagnetic anomaly, and subsequent percussion drilling encountered low-grade, disseminated nickel sulphides. During an option agreement in 1969, WMC carried out some detailed exploration including the drilling of 11 percussion drillholes and 7 diamond drillholes in the north. Between 1969 and 1971 Metals Ex (in joint venture with Freeport and ACM) completed further work including 26 500 m of rotary geochemical drilling and 14 diamond drillholes. Only a few narrow intersections returned average nickel assays in the range 0.5 to 0.8 per cent; the bulk of the mineralization averaged 0.4 per cent nickel. Present title to these tenements is held one third by ACM, one third by Freeport and one third by Amax.

The host ultramafic rock consists largely of lime-green to green-grey and black, medium to coarse-grained serpentinized (lizarditic) dunite to olivinite accompanied by some medium-grained serpentinized pyroxenite. Zones of talc-magnesite rock are developed. The rock types and the style and texture of mineralization are closely comparable with Mount Keith, although a static metamorphic intergrowth of opaque minerals and gangue minerals is well developed at Kingston. Pentlandite, pyrrhotite and magnetite are the chief opaque phases. Minor or accessory pyrite and chalcopyrite occur in some samples.

HONEYMOON WELL PROSPECTS (26°53′00″S, 120°23′00″E)

The Honeymoon Well area is 36 km south-southeast of Wiluna on the southwestern margin of Lake Way. With the exception of one outcrop of lateritized serpentinite and sericitic schist, recognizable weathered bedrock is concealed by about 60 m of laterite, lateritic gravel, lacustrine clay and red-brown quartz sand.

Early exploration by Vam and Delhi included ground magnetic and induced polarization surveys, and the drilling of 65 rotary percussion drillholes (average depth 30 m) most of which probably failed to provide adequate samples of bedrock. Beginning in mid-1971, CRA, in a joint venture with Delhi, drilled 156 percussion drillholes (average depth 59 m) on traverses 610 m apart along strike. This drilling outlined a body of serpentinite (partly talc-carbonated) 10 km long and up to 1 200 m wide. Most geochemical and magnetic anomalies were found along the western and eastern contacts of the ultramafic body. Dips are indicated to be steeply westwards. The country rocks are amphibolites, metamorphosed ultramafic flows, metasediments, and felsic metavolcanic rocks.

The geochemical definition of these anomalies was improved by a programme of reverse circulation rotary drilling (average depth 79 m), and the first three diamond drillholes sited to test the western contact in 1973 intersected low-grade disseminated nickel sulphides in serpentinized (lizarditic) olivinite. A further 16 diamond drillholes were bored into the western contact and an arcuate zone of mineralization (exceeding 1 per cent nickel) was defined, with a strike length of 750 m and a maximum width of 30 m. The best intersection averaged 2.45 per cent nickel over a drilled width of 9 m in drillhole HWD 8 in green-grey serpentinized olivinite partly affected by carbonate alteration. Pentlandite, heazlewoodite and magnetite are the chief opaque minerals; magnetite rims or veins pentlandite. Awaruite, polydymite, pyrite and chalcopyrite may also be present.

On the eastern contact 4 out of 6 diamond drillholes intersected important mineralization over a strike length of 900 m, with the possibility of further mineralization remaining untested to the south. Some of this mineralization may be in the B (basal) zones of ultramafic flows, and consists of pyrrhotite, pentlandite and chalcopyrite. The best intersection averaged 1.44 per cent nickel and 0.1 per cent copper over a drilled width of 32.3 m in drillhole HWD 21, in altered ultramafic flow rocks with an east facing indicated by apparent spinifex and breccia textures.

Demonstrated plus inferred resources are estimated by the author at 10 Mt averaging 1.1 per cent nickel, with a mean Ni:Cu ratio greater than 100, though there is much variability in copper content, with lower ratios typifying sulphides in flow rocks.

MOUNT KEITH - CLIFFS CHARTERHALL PARTNERS PROSPECT (27°18′20″S, 120°33′00″E)

This prospect is 8 km south of the Mount Keith deposit winze and 5 km southeast of Mount Keith homestead. There are some weathered outcrops of felsic metasedimentary or volcaniclastic rocks, and mafic to ultramafic rocks in the area, but superficial deposits conceal much of the geology.

Early work (1970-1972) in the area, by a consortium of Charterhall, Amad, Greenbushes Tin and Ada, concentrated exploration on the southern continuation of the serpentinized dunite-olivinite unit at the Mount Keith deposit. Disseminated nickel sulphides were encountered during diamond drilling but grades were lower than at Mount Keith. Cliffs signed an agreement to earn a 51 per cent interest in the Charterhall consortium's four mineral claims in 1976.

The distribution of ultramafic rocks, as indicated by the previous extensive auger and percussion drilling, was refined by a ground magnetic survey, and a magnetic induced polarization survey was also conducted. In 1977, 20 percussion drillholes (each about 49 m deep) were drilled to test the geophysical anomalies. Three drillholes which encountered coincident nickel-copper geochemical anomalies were then selected for evaluation by diamond drilling which began in September 1978. The first diamond drillhole (CMK 21) intersected 0.3 m of massive pyrite-violarite/pentlandite + magnetite which assayed 3.63 per cent nickel. This mineralization occurred on the eastern contact of a generally talc-carbonated, cumulus-textured serpentinite with a quartz-chlorite-carbonate schist of possible felsic volcaniclastic origin. By the end of 1980 mainly massive nickel sulphides had been intersected in the same contact position in 31 diamond drillholes, to a vertical depth of 500 m and spaced over a strike length of 1850 m. In the northern part of the prospect silicified ultramafics crop out and goethitic gossan occurs along the contact.

The work carried out by Cliffs indicates that the mineralized ultramafic unit is *not* coincident with the extension of the Mount Keith ultramafic unit drilled in the early 1970s by the Charterhall consortium. The mineralized unit is 50 to 150 m thick and occurs up to about 150 m west of the Mount Keith ultramafic unit, but the intervening pale grey-green quartz-chlorite-schists seem to thin southwards and the two ultramafic units may converge. The metasedimentary rock immediately in contact with the mineralization is commonly chlorite rich and may be pyritic with cubes 10 mm in diameter. Relict igneous textures are largely destroyed by talc-carbonate alteration in the mineralized ultramafic unit, but where preserved the close-packed, polygonal, serpentinized olivine textures resemble those at Mount Keith though they are finer grained (drillhole CMK 125). Steep westerly dips are indicated, with less magnesian ultramafic rocks, metabasalt and metasediment overlying the mineralized ultramafic unit, In drillhole CMK 115 spinifex-textured talc-carbonate-chlorite rocks indicate a westward younging for the sequence.

Massive sulphides consist of supergene to primary assemblages of pyrite, violarite, pentlandite, pyrrhotite and chalcopyrite, with a high Fe:Ni ratio being indicated by average nickel assays of 3 to 4 per cent. The average Ni:Cu ratio is about 24. Most massive sulphide intersections are 1 to 2 m thick, but some are much thinner, and the maximum true thickness encountered to date appears to be of the order of 5 m. The sulphide bodies may pinch and swell in similar fashion to the 1A shoot at Agnew. Layering and foliation may be present, and some massive sulphides are better termed breccia sulphide, but much of the massive sulphide lacks any megascopic fabric. In general there is a lack of disseminated nickel sulphide in the overlying ultramafic rock.

The host ultramafic is interpreted as a sill associated with stratigraphically overlying ultramafic volcanics. Inclusions of chloritic rocks and metasediments within the host ultramafic rock are probably xenoliths. The nickel sulphides are then concentrated at the basal contact of the sill. The iron-rich nature of these sulphides could partly result from the assimilation of iron sulphides in chloritic metasediment at the basal contact.

REMAINING DEPOSITS IN NORSEMAN-WILUNA BELT

WEEBO BORE DEPOSIT (28°32′30″S, 120°49′00″E)

Weebo Bore deposit is 27 km south-southeast of the Agnew deposit, 305 km north-northwest of Kalgoorlie and 3 km east of Weebo Bore. The deposit is at the northern end of a complexly faulted appendage of supracrustal rocks where several faults diverge from the Perseverance Fault (Plate 1).

Following the announcement of the discovery of the Agnew deposit in mid-1971, renewed interest was shown in aeromagnetic anomalies along strike. In the same year Newmont entered into an option agreement with the Cullen syndicate who held tenements at Weebo Bore. Using ground magnetic and soil geochemical surveys, with geological mapping and auger drilling programmes, Newmont defined a lenticular zone of serpentinised olivine-rich ultramafic rock 500 m long and up to 80 m wide, and striking north-northwest (Legge, 1975). In November 1971 diamond drillhole WB 1 intersected 84 m of sulphide mineralization in serpentinite, which averaged 0.67 per cent nickel, including 15.2 m averaging 1.15 per cent nickel. This proved to be the best mineralization intersected. A total of 12 diamond drillholes (2 770 m) were drilled on five traverses spaced 122 m apart along strike, but only five drillholes intersected mineralization, from which Newmont inferred resources of 12.6 Mt averaging 0.67 per cent nickel.

The ultramafic host is deeply weathered, but there are some small, poor outcrops on the eastern contact including ferruginous material which assays up to 4 000 ppm nickel. A sample analyzed by Travis and others (1976) contained 0.19 per cent nickel, 0.1 per cent copper, 20 ppb palladium and 6 ppb iridium. At depth the ultramafic lens consists of a core of green to black serpentinized (antigoritic) olivine peridotite to dunite with tremolitic serpentinite and tremolite-chlorite-talc schist developed along the margins and at the strike extremities of the lens (Legge, 1975). The country rocks are hornblende - calcic plagioclase amphibolites to the west, and sodic plagioclase-biotite-chlorite schist (some garnetiferous), with tremolitic ultramafic schists to the east. Layering and schistosity generally dip steeply westwards, and the mineralized ultramafic lens appears to be regionally conformable but locally discordant. Legge (1975) interpreted a moderate plunge to the north-northwest for the lens and also suggested that the lens is truncated at depth (300 m) and displaced eastwards by a west-dipping fault. In 1977 the Cullen syndicate drilled diamond drillhole WB 13 at the northern end of the lens, which, like earlier Newmont drillholes in the same area, failed to encounter the lens at depth.

The primary opaque assemblage (below 135 m depth) consists of pyrite and magnetite which often enclose lesser pentlandite, nickeliferous linnaeite ($(NiCo)_3S_4$), millerite, pyrrhotite and chalcopyrite. The oxidized zone extends to 45 m below surface. The sulphide-oxide aggregates are fine to medium grained and are interstitial to antigorite, being confined to the serpentinite core of the lens (Legge, 1975).

ALLSTATE PROSPECT (28°00′20″S, 120°48′05″E)

This prospect is some 2 to 3 km north-northwest of and along strike from Weebo Bore deposit, in a similar geological setting. A series of thin serpentinite lenses up to 300 m long and 75 m thick occur in felsic schists which represent the attenuated (100 to 300 m wide) continuation of the supracrustal rocks at Weebo Bore. Gneissic granitoid rocks occur to the east and west; the Perseverance Fault forms the boundary between these rocks and the felsic-ultramafic rocks to the west.

Between 1970 and 1974 Allstate, in a joint venture with Oxymin Corporation carried out exploration in the area. Percussion drilling of magnetic and geochemical anomalies encountered weak disseminations of pyrrhotite, pentlandite and chalcopyrite. The best result was an average assay of 0.66 per cent nickel and 0.03 per cent copper over a thin interval of percussion chips. W. Selcast carried out further percussion drilling in 1977 and again low-grade disseminated nickel sulphides were found (up to 1.9 per cent nickel over 4 m), but the mineralization appeared to die out below about 75 m depth.

MOUNT NEWMAN PROSPECT (28°29′30″S, 120°49′00″E)

This prospect is 1 km north-northwest of Mount Newman and 50 km north-northwest of Leonora. The regional geology is described in Chapter 5 under the Mount Clifford group of deposits. The felsic metavolcanic country rocks are laterally associated with the Mount Clifford ultramafic metavolcanic pile which contains small volcanic peridotite-associated nickel deposits. The prospect was discovered by WMC as a result of an ironstone sampling programme which returned a geochemical anomaly of 1 per cent nickel for the area. A small gossan, and relict nickel sulphides in outcrops of blebby serpentinite, were then found. Percussion and diamond drilling defined a plug-like body of granular-textured serpentinized dunite and talc-carbonate rock (366 by 183 m in horizontal dimensions) containing large volumes of low-grade (less than 0.6 per cent nickel) disseminated sulphides, and narrow zones of pyrrhotite-pentlandite veinlets near the western contact. The best diamond drillhole intersection averaged 0.82 per cent nickel over a drilled width of 3.4 m.

SCHMITZ WELL NORTH AND SOUTH PROSPECTS

These prospects are located 59 km northwest of Leonora in lenses of serpentinized peridotite to dunite forming part of a more continuous ultramafic unit, which strikes about 10 degrees east of north and extends between Schmitz Well in the south, and a point 2.5 km west of Six Mile Well in the north. The ultramafic unit is 100 to 300 m wide and occurs along the western contact of a narrow (less than 1 000 m wide) remnant of supracrustal rocks including chloritic schist, metadolerite to metapyroxenite, tremolite-chlorite schist, quartz-mica-actinolite-garnet schist, recrystallized chert, graphitic slate and sulphidic metasediment. A few small serpentinite and talcose serpentinite lenses occur east of the ultramafic unit described. Layering and schistosity generally dip at moderate to steep angles westwards. The remnant is intruded by granitoid rocks and cut by east-northeast-striking Proterozoic gabbroid dykes about 2 km north of Schmitz Well. The strike of the remnant may be controlled by a fault branching away from the Perseverance Fault (Keith-Kilkenny Lineament) in the vicinity of the Webbo Bore deposit (Plate 1).

Schmitz Well South prospect (28°35′10″S, 120°49′20″E) is 1 to 1.5 km north of Schmitz Well, where there is some outcrop of country rocks and lateritized ultramafic rocks. Exploration from late 1969 to early 1972 was carried out by Centaur Mining NL in a joint venture with Wayfarer Ventures Pty Ltd (a subsidiary of Union Corporation of South Africa), and their work included the completion of 30 percussion drillholes and 5 diamond drillholes, mostly collared in the western continuous ultramafic unit, and all inclined eastwards. Two diamond drillholes 600 m apart along strike (SWD 1 and 2) intersected low-grade disseminated nickel sulphides in the lower (eastern) section of the western ultramafic unit at drilled depths of 100 to 120 m. The best intersections averaged 0.74 per cent nickel over 3.4 m (SWD 1) and 1.22 per cent nickel over 1.2 m (SWD 2), with high Ni:Cu ratios. In the second half of 1973 Selco entered into an option agreement with the joint venturers, and carried out auger drilling to define ultramafic bodies to the south of the prospect, which was followed by 18 percussion drillholes in the same area. A further 13 percussion drillholes and one diamond drillhole were sunk in the unexposed area between the south and north prospects to test magnetic anomalies. No encouragement was found in either area.

Schmitz Well North prospect (28°31′55″S, 120°50′05″E) is some 7.5 km north of Schmitz Well, in an area completely covered by superficial deposits, but containing the strike extension of the western ultramafic unit. Peerless Mining Ltd undertook exploration in 1970-1971 and used a ground magnetic survey and auger drilling to define a target area 700 m long and up to 150 m wide. Three vertical diamond drillholes were all reported as encountering disseminated pentlandite in serpentinite; the best intersection was 3.1 m of 1.2 per cent nickel in drillhole 2. Drillhole 3 was sited 465 m north of drillhole 2, and drillhole 1 was collared 93 m to the south.

BLACK SWAN DEPOSIT (30°23′40″S, 121°39′15″E)

The Black Swan deposit is 43 km north-northeast of Kalgoorlie, in a largely concealed, lenticular ultramafic unit which strikes north-northwest (Plate 1). The deposit was discovered and explored by Anglo American in the early 1970s. The petrology of the ultramafic rock and its contained mineralization is described in detail by Groves and others (1974), and a study of the effects of metamorphism on the deposit as deduced from precious metal distribution in described by Keays and others (in prep.). The grade of regional metamorphism is estimated to have attained greenschist-amphibolite facies transitional conditions (Barrett and others, 1977).

An essentially conformable intrusion of cumulus-textured peridotite to dunite converted to serpentinite (antigoritic) and talc-carbonate rock, forms a little-deformed body at least 2 500 m long and 150 to 500 m thick emplaced in tuffaceous felsic metavolcanic rocks. Five serpentinites and talc-carbonates analyzed at the University of Western Australia contained a mean of 45.4 per cent magnesia (volatile-free). Ultramafic and country rocks dip east at moderate to steep angles. Where mineralized the ultramafic unit consists of an east-dipping core of green serpentinite (the dominant host rock) enclosed by talc-magnesite + dolomite rocks. Close-packed, subequant olivine pseudormorphs, 1 to 5 mm in diameter, are well preserved in some serpentinite, but in many serpentinites this texture is partly obliterated by minute chrysotile veinlets or by partial magnesite alteration.

Disseminated sulphides (2 to 10 per cent of the ultramafic host) are patchily distributed in a zone about 400 m long and up to 180 m thick which is some 30 to 50 m above the structural base of the unit. Groves and others (1974) described two textural types of disseminated sulphides: (a) interstitial aggregates between olivine pseudomorphs; and (b) droplet aggregates which are coarser, and are the same size as, and in similar textural positions to, olivine pseudomorphs. Though the mineralogy of individual droplets is more variable, the common opaque assemblage for all mineralization in the primary zone is pyrite with lesser millerite and magnetite, plus minor primary violarite, chalcopyrite and composite chromite-magnetite grains. Pentlandite occurs in some droplet aggregates and some massive sulphide veinlets, and vaesite and polydymite have been recorded from talc-carbonate rocks. Sulphides show static metamorphic intergrowth textures with antigorite and magnesite. Pyrite contains a mean of 0.5 per cent cobalt and 0.3 per cent nickel (Groves and others, 1974). The mean nickel content in 100 per cent sulphides is 15.3 per cent.

Indicated sulphide resources have been estimated at 4.9 Mt averaging 0.89 per cent nickel, using a cut-off figure of 0.50 per cent nickel.

ACRA PROSPECT (30°32′10″S, 122°05′00″E)

Acra (Jubilee) prospect is 64 km east-northeast of Kalgoorlie, and about 1 km south of the Kanowna-Kurnalpi road, near the northern margin of Lake Yindarlgooda. According to Williams (1970) the regional geology of the area is as follows. Intrusive ultramafic rocks are emplaced in the eastern limb of a southeasterly plunging syncline of Kalpini Formation. Dips are steeply inclined. This formation consists mainly of mafic metavolcanic rocks and subordinate pelitic metasedimentary rocks, and is regarded by Williams (1976) as younger than the mafic to ultramafic formations of Kambalda and Widgiemooltha. The ultramafic rocks do crop out in places but are mainly covered by laterite and other superficial deposits through which they are traceable using a magnetometer. Exploration in the area has been undertaken by Jones Mining NL and CRA in the period 1968 to 1972. The main prospect is within MC 175K held by Jones Mining.

The ultramafic body consists of a serpentinized olivine peridotite to dunite, partly converted to talc-magnesite rock, particularly at its margins, which may grade southeastwards into metapyroxenite. The metadunite forms an irregular mass up to 1 000 m wide, but is less than about 200 m thick were mineralized. The northern (presumed basal) contact of the ultramafic unit has been explored by costeaning, auger drilling and geochemical surveys. Gossanous material assaying up to 1.8 per cent nickel and 0.4 per cent copper and containing anomalous amount of palladium and iridium (Travis and others, 1976) is found locally on the contact. The main geochemical anomaly found measured 300 by 20 m and was defined by soil and weathered rock samples containing more than 200 ppm nickel and 100 ppm copper, including two peak values of 4 000 to 6 000 ppm nickel with high copper.

Of the twelve diamond drillholes put down by Jones Mining to test the contact zone the best intersection assayed 4.36 per cent nickel and 0.04 per cent copper over 0.27 m (DDH AD 4).

Few of these drillholes penetrated very far into the metadunite. Diamond drillhole AD 13, drilled by CRA to the north of the geochemical anomaly, intersected several zones of disseminated sulphides in the lower 120 m of the ultramafic unit. These zones assayed 0.53 to 0.69 per cent nickel over widths up to 21 m. The opaque minerals are magnetite, pyrite, pyrrhotite, chalcopyrite, millerite and siegenite (nickel-cobalt sulphide) occurring as disseminations and veinlets.

QUEEN VICTORIA ROCKS PROSPECT (31°18′30″S, 120°52′10″E)

This prospect is 48 km southwest of Coolgardie in a small remnant of mafic to ultramafic rocks and quartz-biotite schist in granitoid terrain (Fig. 65). Exploration was carried out by Spargos during 1971-1973: 14 diamond drillholes (3 637 m total) were completed and a lens of coarse-grained polygonal-textured metadunite 1 370 m long and up to 690 m wide was defined The dunite is serpentinized and may contain anthophyllite; metamorphic orthopyroxene occurs in some ultramafic rocks. High amphibolite facies regional metamorphism is therefore indicated. The best sulphide intersections obtained were 3.05 m averaging 0.83 per cent nickel (DDH 4) and 6.10 m averaging 0.96 per cent nickel (DDH 15).

FORRESTANIA GROUP

GEOLOGY

GENERAL

The deposits of the Forrestania group are located in the southern quarter of the Southern Cross – Forrestania supracrustal belt, a narrow curvilinear belt some 300 km long, and oriented between north and north-northwest (Plate 1). All deposits of the group except the Mount Hope and Antimony Nickel prospects are shown on Figure 22, which summarizes the interpreted regional geology. Outcrop is generally poor, except for variable weathered banded iron-formations, which form narrow hogsback ridges throughout the area, and some amphibolite and metasedimentary rocks. Olivine-rich ultramafic rocks are rarely exposed except as deeply weathered or lateritized material.

Most geological information stems from the exploration carried out by Amax (in joint ventures with Amoco and Endeavour), mainly in the period 1969 to 1978, and is contained in numerous unpublished reports, principally by G.R. Day, K.S. Docking, K.G. McKay, K. Robinson and W.K. Witt. There is little published information and what is available deals with specialised aspects (e.g. Keays and Davison, 1976; Leggo and McKay, 1980). Unpublished theses by Witt (1972), Lawn (1977), and Purvis (1978), deal mainly with petrological aspects of the Middle Ironcap, North Ironcap and Digger Rocks areas respectively. Some general features of the host rocks and mineralization are referred to by Binns and others (1977) and Barrett and others (1977). Chin and others (in prep.) describe the regional geology.

STRATIGRAPHY AND STRUCTURE

McKay (1973) suggested that the supracrustal rocks have been regionally folded into a shallowly north-plunging syncline, with a semi-pelitic metasedimentary sequence occupying the core of the syncline and overlying an older mafic to ultramafic sequence which contains the mineralized metadunites (Fig. 22). A tentative stratigraphic scheme is given in Table 22; the main uncertainty is the detailed correlation of the west and east limbs of the syncline even though in both places nickel mineralization of importance is restricted to the structually lowest ultramafic formation (Leggo and McKay, 1980). Strike faulting could partly account for the apparent absence of well-developed upper ultramafic formations on the west limb (Fig. 22).

The footwall metasediments are different in character: those on the west limb appear similar to psammitic metasediments described by Gee (1979) from the Southern Cross area. He regarded these psammitic metasediments as forming the base of the supracrustal succession at Southern Cross where they are succeeded by a mafic to ultramafic sequence which is contiguous with the east limb of the syncline at Forrestania. Gee (1979) placed a sequence of pelitic metasediments, lithologically similar to the hangingwall metasediments at Forrestania, above the mafic to ultramafic sequence.

The dip of the layering is consistent with the presence of a syncline at least as far south as North Endeavour (Fig. 22). Further south, the western limb in particular appears

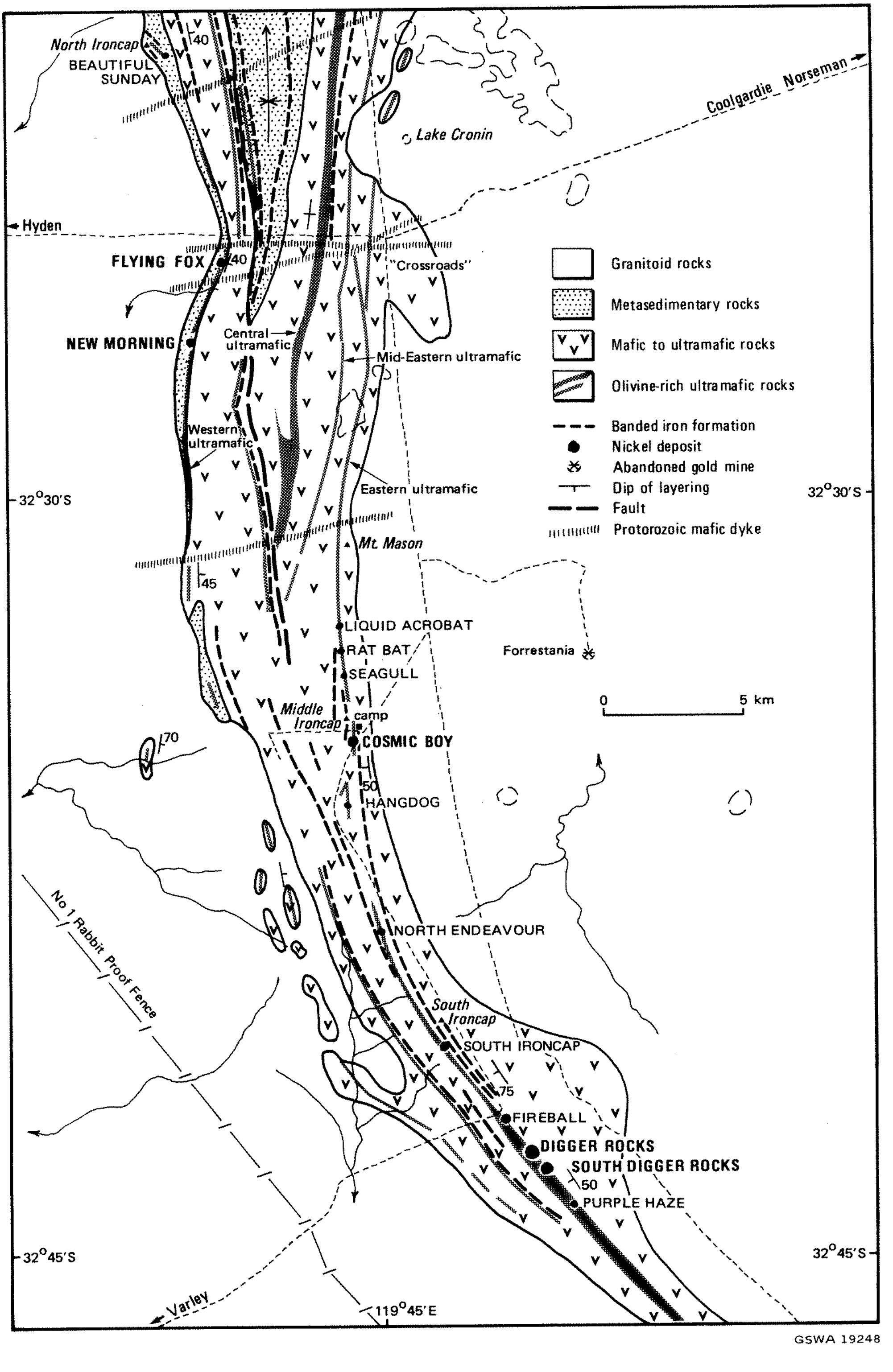

Figure 22. Geological map of the Forrestania group of nickel deposits, mainly based on data from Amax Exploration (Australia) Inc.

to be increasingly removed by a combination of granitoid intrusion and possible strike faulting. The east limb, to the north of Mount Mason, is vertical to steeply west- or east-dipping (i.e. overturned), whereas the west limb remains moderately east-dipping.

TABLE 22. GENERALIZED TENTATIVE STRATIGRAPHY OF THE FORRESTANIA REGION

Informal information	Rock types	Approx thickn'ss (m)
(9) Hangingwall metasediments	Layered semi-pelitic schist containing quartz with combinations of biotite, muscovite, sodic plagioclase, andalusite, sillimanite, cordierite, almandine	2000
(8) Basic amphibolite	Hornblende-calcic plagioclase $\mp$ biotite $\mp$ quartz $\mp$ epidote $\mp$ almandine; many units	?200
(7) Central ultramafic (poorly developed on WEST LIMB)	Tremolite-chlorite + serpentine, talc; some spinifex-textured rocks; some amphibolite, interflow chert, black slate, sulphidic and quartz-biotite-amphibole metasediment; basal metadunite with rare nickel occurrences	600
(6) Basic amphibolite	As for (8)	1200
(5) Mid-eastern ultramafic	As for (7); poorly developed on WEST LIMB	200
(4) Basic amphibolite	As for (8)	2000
(3) Eastern ultramafic (EAST LIMB) or Western ultramafic (WEST LIMB)	As for (7) with more numerous and thicker lenses of metadunite to olivinite at or near the base, which are host to many nickel deposits	50-1500
(2) Footwall metasediments	EAST LIMB Quartz-chlorite-biotite-muscovite schist, quartz-biotite-amphibole schist and varieties with andalusite, sillimanite, staurolite, garnet, diopside	0-200
	WEST LIMB Siliceous quartz-muscovite-sillimanite schist and quartzite	300
(1) Basic amphibolite (EAST LIMB ONLY)	As for (8)	500
Granitoid rocks, intrusive into most of the above formations		

Notes:

1. Laminated quartz-magnetite $\mp$ grunerite $\mp$ hornblende $\mp$ iron sulphide (BIF) and other quartz-amphibole metasediments, up to 50 m thick, occur throughout the succession and particularly in association with the ultramafic formations.
2. West and east limb refer to the major, north plunging syncline (see Fig. 22).
3. Data from Amax Exploration (Australia) Inc.

In common with the Norseman-Wiluna belt, there is evidence that the location of olivine-rich ultramafic lenses (10 to 500 m thick and up to 3 km long at Forrestania) is stratigraphically controlled, despite the lenses being intrusive and locally discordant. Another comparable feature is the spatial association of the lenses at Forrestania with ultramafic volcanic rocks in the stratigraphic hangingwall.

The olivine-rich ultramafic lenses are petrologically very like those described from the Norseman-Wiluna belt, (particularly the Perseverance ultramafic), except that little-serpentinized dunite to olivinite is abundant at Forrestania. Static to dynamic igneous textures are common, being represented by medium- to coarse-grained, close-packed, generally colourless, subequant olivine of which varying proportions have been fractured and granulated. This olivine is regarded as reheated, but not recrystallized, igneous olivine. Oriented fracture sets, serpentine veinlets and olivine remnants produce a foliation. Coarse-grained porphyroblasts of anthophyllite and finer grained talc, are superimposed on cumulus-textured olivine aggregates. Static to dynamic metamorphic textures, represented by medium- to coarse-grained, bladed or ovoid metamorphic (i.e. recrystallized) olivine porphyroblasts, are less common but are found to alternate with cumulus-textured olivine aggregates. Variable amounts of fine- to medium-grained talc, chlorite, tremolite, anthophyllite and carbonate accompany igneous or metamorphic olivine, or serpentine pseudomorphing olivine. Metamorphic enstatite has been reported from a few lenses (Barrett and others, 1977).

Dynamic metamorphic textures characterize most of the country rocks. Critical mineral assemblages in the country rocks and the olivine-rich ultramafic lenses indicate that high amphibolite facies conditions were attained during prograde regional metamorphism (Barrett and others, 1977). Retrogressive metamorphism is marked by the alteration of metamorphic olivine to serpentine and anthophyllite to talc or serpentine.

East-striking Proterozoic mafic dykes cut across the supracrustal belt, and are commonest in the north.

MINERALIZATION

GENERAL

Exploration interest in the Forrestania region began with the discovery by a prospector of gossan at New Morning deposit in October 1969 (Leggo and McKay, 1980). The ground was pegged by Amax, who, in joint venture with Amoco (49 per cent), decided to explore a large part of the region. An extensive ironstone and rock-chip sampling programme begun in 1971 led to the discovery of mineralization at Cosmic Boy, Digger Rocks, Mount Hope, Liquid Acrobat and Seagull. Guided by geological and geophysical surveys, exploration in unexposed and deeply weathered areas proceeded by rotary airblast (RAB) geochemical drilling on a 122 m by 15 m spacing (7.6 m on ultramafic contacts) to an average depth of 15 m, with a total of more than 45 000 drill holes being completed (Leggo and McKay, 1980). Drilling on 61 m by 7.6 m spacing located the concealed Flying Fox deposit. Leggo and McKay (1980) reported that copper is the most diagnostic element in weathered ultramafic rock, contents in excess of 200 ppm being reliable indicators of subjacent nickel sulphides.

The Digger Rocks – Hang Dog area was explored by Amax and Amoco in joint venture with Endeavour.

Nickel sulphide mineralization is widespread as bodies of low grade (0.5 to 1.0 per cent nickel) disseminations 5 m to 30 m thick, in the central portions of the dunite-olivinite lenses. This style of mineralization can be compared with the Mount Keith and Six Mile Well deposit. However, all the calculated nickel sulphide resources of 11 Mt averaging 2.31 per cent nickel (at 1 per cent nickel cut-off) are contained in four deposits — Cosmic Boy, Digger Rocks/South Digger Rocks, Flying Fox and New Morning — which consist mainly of sulphides concentrated at the structural (and probable stratigraphic) base of the host ultramafic (Table 23). These deposits are made up of disseminated, breccia, massive and minor triangular-textured (sulphides occupying triangular volumes between bladed, metamorphic olivine) ores. Massive and breccia ores are typically near the base of the ultramafic, either (i) at the basal contact; (ii) within the disseminated ore; or (iii) offset into the footwall metasediment. All three situations can be found in the New Morning deposit.

The major deposits on the east limb of the syncline, Cosmic Boy and Digger Rocks, are larger but contain less of their tonnage in the form of massive ores, and are therefore of lower bulk tenor compared with the Flying Fox and New Morning deposits on the west limb (Table 23). There is no important variation in sulphide mineralogy in these deposits except in the pyrrhotite:pentlandite ratio, and most of the disseminated ores have mean bulk Ni:Cu ratios between 19 and 21. Nickel-rich sulphides occur in some of the small, low-grade deposits, notably Mount Hope (heazlewoodite, millerite) and Beautiful Sunday (millerite). Nickel arsenides are rare, being found in some rocks subjected to strong talc-carbonate alteration (e.g Crossroads area).

Sulphide textures in general resemble those at Agnew, but important differences are the lack of deformation textures in pyrrhotite (which is, however, conspicuously cleaved), and the poor development of very fine-grained sulphides dispersed throughout olivine or serpentine. Annealing-recrystallization textures are not notable. Disseminated sulphides are mainly restricted to aggregates which have smooth, lobate contacts with enclosing olivine grains or olivine pseudomorphs. The olivines themselves form elongate, rounded prisms in contact with the sulphides (Fig. 94H). Metamorphic recrystallization and intergrowth of sulphides and gangue is rare. The cracking and granulation present in the olivine aggregates are commonly pervasive and fracture pentlandite in particular and also chromite (Fig. 95B). Gangue minerals, pyrite, or magnetite in some serpentinites, fill the cracks in pentlandite. Anthophyllite porphyroblasts are also fractured and may contain sulphide veinlets or intergrowths. Foliation and mineralogical layering are not normally developed in massive or breccia ore.

The first deposits described are in the east limb, followed by those in the west limb, and from south to north in each case. Evaluation of the major deposits has not proceeded beyond the diamond drilling stage.

DIGGER ROCKS AND SOUTH DIGGER ROCKS DEPOSITS

General

Digger Rocks (South Endeavour) deposit (32°42′00″S, 119°48′10″E) was discovered in 1971 as a result of the ironstone sampling programme. The deposit is located 82 km east-southeast of Hyden and 5 km southeast of South Ironcap Hill (Fig. 22). South Digger Rocks deposit (32°43′20″S, 119°48′25″E) is a blind southeastward extension of the main deposit, discovered during scout drilling along strike. There is a small, deeply weathered outcrop at Digger Rocks and sampling of the coarse fraction

TABLE 23. FEATURES OF THE MAJOR DEPOSITS OF THE FORRESTANIA GROUP

	Cosmic Boy Basal zone	 Upper zone	Digger Rocks	South Digger Rocks	Flying Fox	New Morning
Ore type	Disseminated, massive	Disseminated	Disseminated, massive	Disseminated	Massive, disseminated	Massive, disseminated
Ore position	Near-basal	Hangingwall, internal	Basal, internal	Near-basal	Basal, offset	Basal, offset, internal
Primary mineralogy[1]	pn-po-py + cpy ∓ ml	pn-po-py + cpy	po + pn + py + cpy	po-pn + py + cpy	po + pn + py + cpy	po + pn + py + cpy
Supergene mineralogy[1]	vl-py + ms		vl-py	py + vl	py + vl	py + vl
Base of oxidized zone	50 m		50 m		90-120 m	50-70m
Base of violarite-pyrite zone	300 m		100 m		200 m	200 m
Ore thickness	2-16 m	2-6 m	3-50 m	15 m	1-5 m	1-19 m
Strike length	800 m		400 m	490 m	600 m	580 m
Vertical depth extent	180-450 m		250 m	150-480 m	100-300 m	380 m
Range of nickel tenor	1.0-5.6%	1.0-3.5%	Dissem: 0.6-3.0% mass: 3.0-9.0%	1.3-1.7%	Dissem: 0.7-3.0% mass: 1-12%	Dissem: 1-2.5% mass: 6-9%
Ni:Cu ratio	20		Internal: 75 basal dissem: 21	35	Dissem: 19 mass: 45	Dissem: 20 (basal), 76 (internal) mass: 37
Ni:Co ratio	72		Internal: 37 basal dissem: 31		Dissem: 52 mass: 67	Dissem: 28 (basal), 61 (internal) mass: 43
Indicated resource[2] and mean nickel tenor	3.37 Mt 2.87%	2.096 Mt 2.12%	1.232 Mt 2.21%	3.2 Mt 1.41%	0.53 Mt 4.6%	0.569 Mt 2.91%
Contained nickel (and in parentheses the deposit category[3])	96 719 t (3)	44 435 t (4)	27 227 (4)	45 120 (4)	24 380 (4)	16 571 (4)

Notes:

1. Mineral abbreviations are—
pn—pentlandite, po—pyrrhotite, py—pyrite, cpy—chalcopyrite, vl—violarite, ml—millerite, ms—marcasite.
2. Resource figures are calculated using a cut-off of 1 per cent nickel.
3. Deposit categories are as defined on Figure 16.
4. Data are from Leggo and McKay (1980), with additions.

of residual soils produced a strong, coincident nickel-copper anomaly (highest: 2050 ppm and 190 ppm respectively) over the subcropping mineralized unit (Leggo and McKay, 1980). Gossans contain up to 1.5 per cent nickel and 2 700 ppm copper. Indicated resources for Digger Rocks and indicated plus inferred resources for South Digger Rocks are given in Table 23, based on 33 and 10 diamond drillholes respectively.

Stratigraphy and structure

Digger Rocks occurs at about the mid-point of an ultramafic body which has been traced for some 30 km along strike, and which is probably a southern extension of the eastern ultramafic unit (Fig. 22). The unit reaches its maximum thickness of about 400 m in a lens some 2 km long at Digger Rocks. McKay (1973) described the stratigraphy of the ultramafic unit (as summarized in Table 24). There is little textural difference between olivine peridotite and dunitic units: both are cumulus-textured and consist of medium- to coarse-grained, granulated, coulourless igneous olivine accompanied by minor serpentine, talc, anthophyllite porphyroblasts and chlorite. Bladed metamorphic olivine is of rare, patchy development. The mean magnesia content (volatile-free) of 20 samples of dunite analyzed by Purvis (1978) is 47.7 per cent; 20 samples of olivine peridotite returned means of 38.2 per cent for olivine + anthophyllite rocks and 43.6 per cent for olivine + talc rocks. The main ultramafic host (units (6), (7), (8) and (9) in Table 24) can be summarized as an olivine peridotite with a thin dunitic core. A thin, metamorphosed banded iron-formation (BIF) separates the main ultramafic body from a basal, differentiated metaperidotite, and both ultramafic units transect a thick BIF in the north (Fig. 23). The stratigraphy is further complicated by a later, metapyroxenitic intrusion emplaced into the base of the main ultramafic body (Fig. 23, cross section). Tremolitic metasomatic reaction zones may occur at contacts between olivine-rich ultramafic rocks and BIF or metasediment.

The dip averages about 50 degrees towards the southwest at Digger Rocks, steepening to 60 to 75 degrees at South Digger Rocks. Besides granulation and fracturing of the olivine and some thin intervals of foliated serpentinite little penetrative deformation has affected the main ultramafic body.

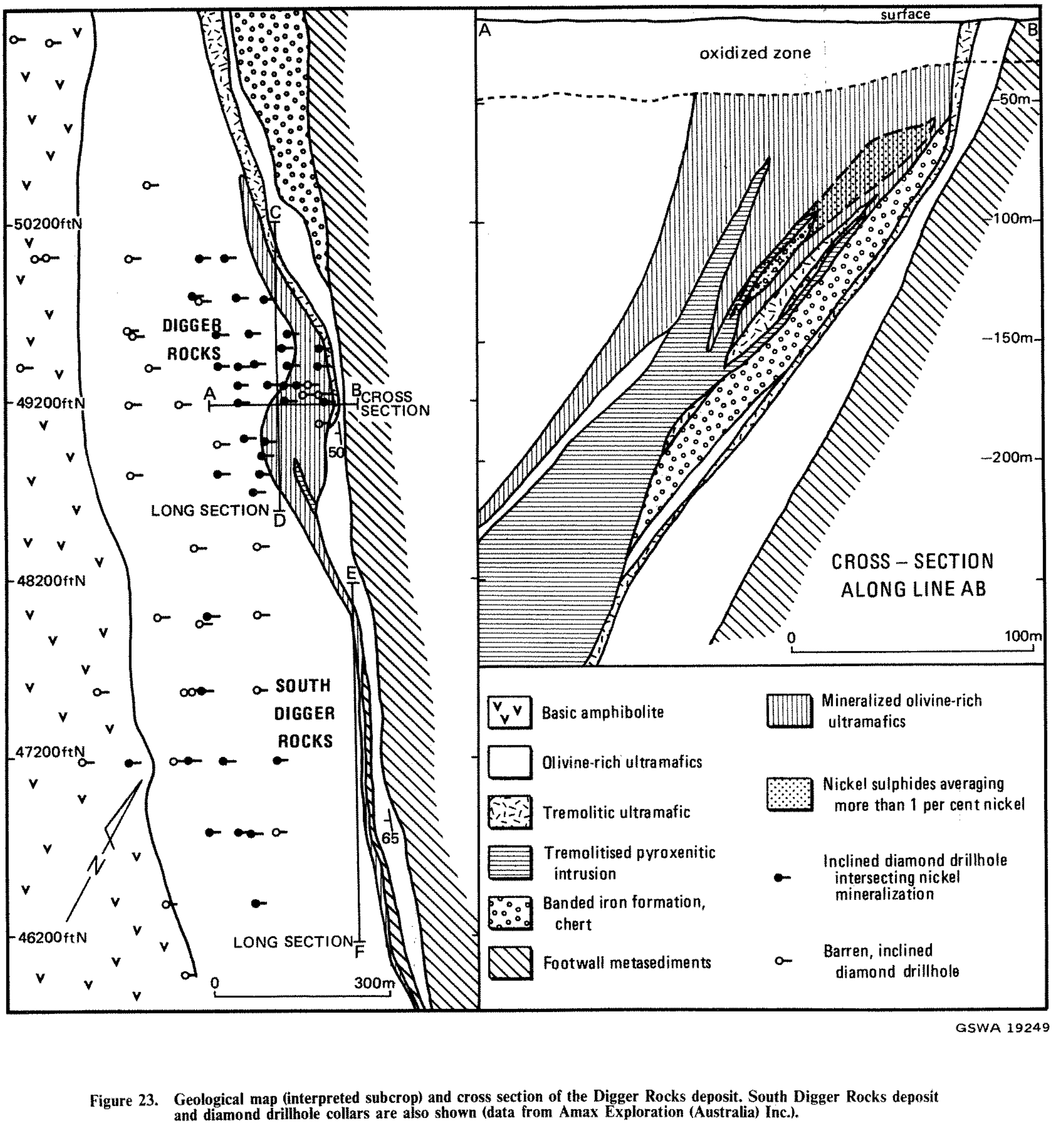

Figure 23. Geological map (interpreted subcrop) and cross section of the Digger Rocks deposit. South Digger Rocks deposit and diamond drillhole collars are also shown (data from Amax Exploration (Australia) Inc.).

TABLE 24. GENERALIZED STRATIGRAPHY AT DIGGER ROCKS DEPOSIT, FORRESTANIA GROUP

Unit	Lithology	Thickness (m)
(11) Hangingwall basic amphibolite	Hornblende-calcic plagioclase + quartz + biotite	
(10) Upper contact basic schist		15-46
(9) Upper barren hanging-wall meta-olivine peridotite	Granular or bladed olivine + talc + anthophyllite + carbonate	122-316
(8) Hangingwall metadunite	Partly serpentinized olivine + talc + anthophyllite, granular or bladed olivine, contains low grade disseminated nickel sulphides	21-50
(7) Lower barren hanging-wall meta-olivine peridotite	As for (9)	Included with (9)
(6) Main meta-olivine peridotite	Similar to (8), mainly granular textured, contains bulk of nickel sulphides	6-107
(5) Banded iron-formation (metamorphosed)	Quartz-magnetite + hornblende ∓ grunerite ∓ ferrosalite ∓ chlorite ∓ garnet	0-20
(4) Tremolitized pyroxenitic intrusion	Tremolite/actinolite + chlorite	0-49
(3) Footwall barren metaperidotite	Differentiated intrustion (?) pyroxenitic margins, peridotitic core; olivine, orthopyroxene, tremolite, anthophyllite rocks	31-61
(2) Footwall meta-sediments	BIF-chert on top contact in north; quartz-biotite schists	61-183
(1) Basal basic amphibolite	As for (11)	

Data are from McKay (1973)

Ore distribution and petrology

The distribution of the mineralized olivine peridotite (unit (6) in Table 24) is indicated in Figure 23, which shows the relative positions of Digger Rocks and South Digger Rocks deposits. Nickel sulphide mineralization averaging more than 1 per cent nickel is more restricted in distribution as illustrated by Figures 23 (cross section) and 24. This higher grade mineralization is only found near the base of unit (6) in both deposits, but mineralization averaging 0.6 to 0.8 per cent nickel occurs over thicknesses of 5 to 20 m and a strike length of 183 m in the dunitic core (unit (8)) at Digger Rocks, and is known as Digger Rocks hangingwall (denoted as 'internal' in Table 23). Low-grade (0.5 to 0.6 per cent nickel) internal sulphide mineralization has also been encountered in drilling of the ultramafic unit, 2.8 to 5.1 km southeast of Digger Rocks at a prospect known as Purple Haze (Fig. 22).

Digger Rocks deposit plunges northwestwards at 40 to 45 degrees. Most of the higher grade disseminated and matrix to massive ore is confined to a lens up to 18 m thick, above 100 m vertical depth, and consequently is in the violarite-pyrite zones. Some sulphides have been mobilized into BIF and the metapyroxenite intrusion (Fig. 23). The mineralized olivine peridotite thins downwards and is 10 to 15 m thick at 215 m vertical depth. Details of the mineralogy and chemistry of the ore are given in Table 23. The pyrrhotite-pentlandite ratio in disseminated ore varies from 1 to 3.

The extent of the South Digger Rocks deposit is poorly defined and mineralization is restricted to vertical depths greater than 150 m (Fig. 24). Though apparently larger in terms of contained nickel than Digger Rocks, the ore tenor is lower because of the absence of sulphide-rich disseminated ore, and of matrix to massive ore (Table 23). The upper and lower limits to mineralization are sharper than at Digger Rocks: nickel declines from 1 per cent to background values over about 1.5 m. The pyrrhotite:pentlandite ratio is about unity.

Granular olivine and prismatic anthophyllite porphyroblasts are fractured by reticulated networks of cracks which also penetrate pentlandite and to a lesser extent the cleaved but otherwise little deformed pyrrhotite. Pentlandite-pyrrhotite aggregates are fine- to medium-grained and lobate in outline, being interstitial to rounded prismatic olivine. Magnetite may be important in more serpentinized dunite-olivinite. Foliation is rarely developed, except in some massive ore.

FIREBALL PROSPECT (32°42′20″S, 119°47′50″E)

Fireball prospect is the name given to mineralization that is probably a northwesterly continuation some 1 200 m along strike of the Digger Rocks hangingwall mineralization described above. Diamond drilling totalling 2 188 m has been carried out by Amax. Three diamond drillholes (FBD 2, 5 and 10) intersected low-grade disseminated sulphides assaying 0.5 to 0.8 per cent nickel over 15 to 50 m, the best intersection being 7.5 m averaging 0.9 per cent nickel. Pentlandite aggregates are densely cracked and lobate in outline. The olivine-rich ultramafic host is some 120 m thick and contains granulated, colourless igneous olivine with anthophyllite porphyroblasts superimposed. There is a close resemblance with the dunitic core of the Perseverance ultramafic lens.

SOUTH IRONCAP PROSPECT (32°40′50″S, 119°47′15″E)

Similar low-grade mineralization has been found during diamond drilling (1 750 m total) at South Ironcap prospect, 4 km along strike to the northwest of Digger Rocks. Irregularly distributed disseminated sulphides contain 0.5 to 0.85 per cent nickel over a thickness of 5 to 25 m in single or multiple zones. The ultramafic host, equivalent to that at Digger Rocks, consists mainly of close packed, polygonal, medium-grained, granulated igneous olivine with talc and lesser coarse anthophyllite in places. Interstitial pentlandite-pyrite aggegates are cracked and lobate. Bladed metamorphic olivine is developed in sparse patches. Several recrystallized quartz veins with marginal talc-tremolite metasomatic reaction zones cut the metadunite. A thick body of BIF (unit (2) of Table 24) stands up as a ridge including South Ironcap on the northern (footwall) side of the ultramafic unit.

NORTH ENDEAVOUR AND HANG DOG PROSPECTS

At North Endeavour prospect (32°38′40″S, 119°45′00″E), centred 8.6 km northwest of Digger Rocks, small gossans with boxwork textures assaying 1.65 per cent nickel and 0.15 per cent copper were found in outcrops of silicified and ferruginized schistose ultramafic rock. Two thin ultramafic units, 15 to 70 m thick, are separated by basic amphibolite; the western unit is continuous with the mineralized ultramafic unit at South Ironcap. Diamond drilling (1 795 m total) encountered foliated olivine-rich ultramafic rocks containing serpentinized bladed metamorphic olivine accompanied by talc and minor carbonate, chlorite and tremolite. Cumulus-textured metadunite is subordinate. Three diamond drillholes (FD1, NED1 and 2) completed at and near the gossan site intersected 1.5 and 4.6 m widths of pyrrhotite-rich sulphides in these rocks, averaging 0.7 to 0.9 per cent nickel. Another drillhole (NED 7) sunk 1 700 m along strike to the southeast intersected 8.92 m averaging 0.79 per cent nickel and 0.83 m of pyrrhotitic breccia sulphide at the basal (eastern) contact. Two drillholes (NED 5, 15) 2 km north of the gossan site intersected pyrrhotite-rich breccia sulphides in 15 to 20 cm thick veins on the basal contact of the ultramafic unit; one vein contained 2.05 per cent nickel.

These two northern drillholes are sited at an apparent break in the Eastern ultramafic unit; some 2.6 km to the north-northwest two short ultramafic lenses 10 to 85 m thick, occur in an area known as Hang Dog prospect (32°36′20″S, 119°44′10″E). Two diamond drillholes (HDD 1 and 2) intersected pyrrhotitic disseminated mineralization assaying up to 0.6 per cent nickel over a few metres.

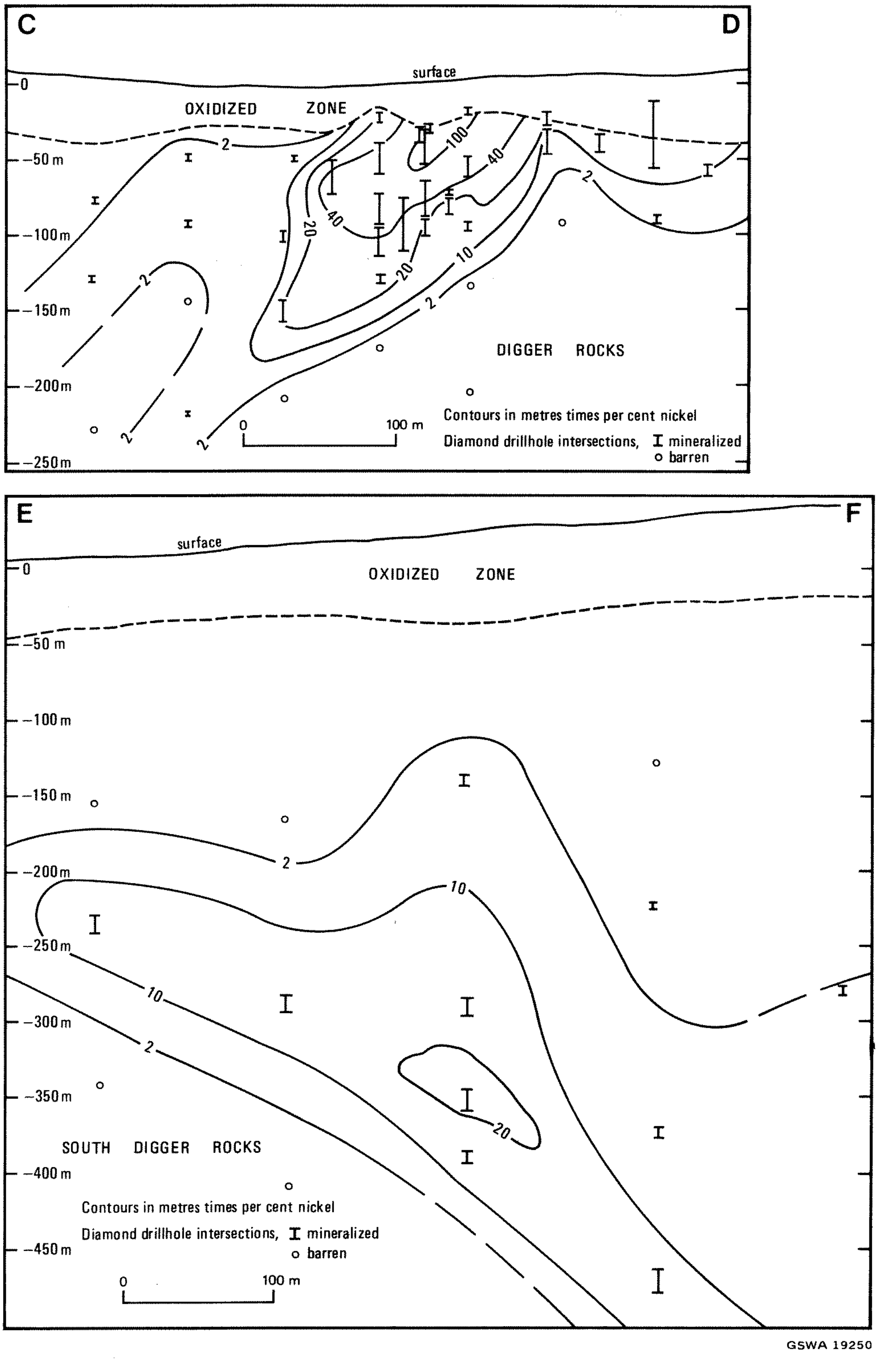

Figure 24. Vertical longitudinal section projections (looking east) of the Digger Rocks and South Digger Rocks deposits showing distribution of nickel sulphides at 1 per cent nickel cut-off. Locations of sections are shown on Figure 23 (data from Amax Exploration (Australia) Inc.).

COSMIC BOY DEPOSIT (32°34′50″S, 119°44′20″E.

Cosmic Boy deposit was discovered in 1971 as a result of the ironstone sampling programme which detected material derived from the subcrop of the 'upper zone' of the deposit. The 'basal zone' mineralization has no surface expression. The deposit is located 84 km east of Hyden and 1.5 km south of Middle Ironcap hill. Drill-indicated resources are given in Table 23.

Geological continuity with the deposits described to the south is provided by a persistent BIF (unit (2) of Tables 24 and 25) occurring in the footwall of the ultramafic unit at Cosmic Boy. Day and others (1973) described the stratigraphy, which is summarized in Table 25. Ten metadunites from Cosmic Boy average 46.5 per cent magnesia on a volatile-free basis (unpublished data, University of Western Australia). The ultramafic host is 2.2 km long and wedges out into BIF to the north and south; it averages 70 to 95 m in thickness and dips west at 45 to 60 degrees.

TABLE 25. GENERALIZED STRATIGRAPHY AT THE COSMIC BOY DEPOSIT, FORRESTANIA GROUP

Unit	Lithology	Thickness (m)
(10) Magnesian metabasalt	Tremolite + chlorite ∓ olivine foliated rocks, basaltic to picritic; rare spinifex-textured rocks	100
(9) BIF or chert (metamorphosed)	Finely laminated quartz-magnetite ∓ grunerite, some pyrrhotite or pyrite rich layers	40-50
(8) Mafic metasediments	Foliated biotitic, feldspathic, quartzose, garnetiferous, layered amphibolite, with Fe-Mg-Ca carbonates + dioposide; probably volcanic in part	100-130
(7) Metadunite	Partly serpentinized metamorphic olivine + talc + carbonate + chlorite + anthophyllite + tremolite; some foliated	0-50
(6) Mafic metasediments + BIF	As for (8) and (9)	60-90
(5) Metadunite	As for (7), but with some granular olivine textures; includes thin intervals of BIF and mafic metasediment. Upper Zone: disseminated nickel sulphides	15-25
(4) Mafic metasediments + BIF	As for (8) and (9)	30-50
(3) Metadunite	Mainly granular olivine with subordinate talc, serpentine, chlorite, brucite, some patchy anthophyllite development; includes thin intervals of BIF and mafic metasediment. Basal zone: disseminated-massive nickel sulphides	15-60
(2) BIF (metamorphosed)	Finely laminated quartz-magnetite ∓ grunerite ∓ hornblende	40
(1) Mafic metasediments	As for (8)	

Data are from Day and others (1973)

The mineralization is concentrated in the central one-third of the strike length of the ultramafic unit. A low northerly plunge is indicated for the basal zone, which may have some relation to north-plunging folds in the BIF at Middle Ironcap. Compared with the upper zone, the basal zone mineralization is higher grade, more continuous and more extensive, but it has not been intersected below a vertical depth of 450 m (Table 23). A section of the basal zone between 270 and 330 m vertical depth is poorly mineralized and coincides with an inflexion upwards in the footwall of the ultramafic host. Disseminated sulphides make up the bulk of the basal zone; thin lenses and veins of matrix to massive sulphides occur in disseminated sulphides. Patchy, disseminated, and triangular-textured sulphides characterize the upper zone.

Ore mineralogy is summarized in Table 23. Granular magnetite is abundant in the basal zone compared with the upper zone. Millerite-pyrite-magnetite may develop locally in the basal zone. Pyrrhotite is generally cleaved and contains a few kink bands but is generally little strained. Pentlandite and pyrite are cracked by the fractures which granulate the olivine aggregates (Fig. 95B). Magnetite may rim and/or vein pentlandite. In triangular-textured ore sulphides may be intergrown with talc and tremolite.

SEAGULL PROSPECT (32°33′30″S, 119°44′10″E)

Seagull prospect is 800 m north of Middle Ironcap, in a lens of ultramafic rocks which is 1 200 m long and up to 150 m thick. The internal stratigraphy of the lens is complex: foliated tremolite-chlorite + magnetite rocks, serpentinites, quartz-magnetite BIF, and serpentine-talc rocks are interleaved along sharp contacts. Serpentinized bladed metamorphic olivine + talc rock contains low-grade (0.5 per cent nickel) disseminated nickel sulphides over widths of up to 16 m, and mineralization averaging 1.2 to 1.4 per cent nickel over less than half that width. The better grade mineralization appears to have a strike of about 200 m. There is some surface gossanous expression of this mineralization. Amax have estimated resources at 970 000 t averaging 1.31 per cent nickel (1 per cent cut-off).

RATBAT PROSPECT (32°33′00″S, 119°44′10″E)

Some 2 km north of Middle ironcap, Ratbat prospect occurs in an ultramafic unit up to 45 m thick which is slightly *en echelon* to the ultramafic lens at Seagull prospect. Several portions of quartz-magnetite BIF are interleaved with foliated, partly serpentinized bladed olivine + anthophyllite + chlorite + talc + carbonte metadunite and serpentine-tremolite rocks. Mineralization in excess of 1 per cent nickel occurs in thin (10 m) hangingwall (western) components of the ultramafic, over a strike length of about 100 m and a width of up to 7 m. Resources have been estimated at 250 000 t averaging 1.1 per cent nickel (1 per cent cut-off).

LIQUID ACROBAT DEPOSIT (32°32′30″S, 119°44′10″E)

Liquid Acrobat deposit is 3 km north of Middle Ironcap in an ultramafic host which is continuous with that at Ratbat prospect, and which dips west at about 35 degrees. The ultramafic unit is lenticular, 10 to 60 m thick, and consists mainly of close-packed, medium- to coarse-grained, granulated olivine with minor talc, serpentine, chlorite and anthophyllite. Bladed metamorphic olivine is subordinate and patchily developed. Some thin zones of ultramafic rock are foliated. Foliated plagioclase amphibolite forms the footwall, and quartz-magnetite ∓ grunerite ∓ carbonate BIF with some pyrrhotite-pyrite layers occurs in the hangingwall with amphbibolite, and tremolite-chlorite + carbonate rock (some spinifex-textured).

Disseminated sulphides are present within the metadunite, with no concentration at the contacts, over a strike length of 1 200 m in a zone up to 16.5 m thick. Average grades are 0.6 to 1.0 per cent nickel with some stringers containing up to 3.7 per cent nickel. Pyrite and pyrrhotite, with subordinate pentlandite and a little chalcopyrite, are altered to violarite, pyrite and marcasite in weathered rock.

Sulphide aggregates are typically lobate, although talc, chlorite, or serpentine may project into the aggregates. Pentlandite is thoroughly fractured and may be veined by pyrite (Fig. 94H). Unzoned chromite is also cracked. Fine-grained chalcopyrite is intergrown with pyrite. Sulphides and chromite have recrystallized within anthophyllite porphyroblasts. Resources have been estimated at 670 000 t averaging 1.36 per cent nickel (1 per cent cut-off).

CROSSROADS PROSPECT (32°25′10″S, 119°44′50″E)

This prospect is 18 km north of Middle Ironcap near the intersection of the Hyden-Norseman and Digger Rocks - Marvel Loch roads (Fig. 22) Lenticular ultramafic bodies representing the Eastern ultramafic unit can be traced northwards from the Middle Ironcap area into the Crossroads area where two magnetically prominent Proterozoic basic dykes cross. The Eastern ultramafic unit is near-vertical and consists of lenses up to 80 m thick of talc-carbonate + serpentine + chlorite + tremolite rock interlayered with mafic schists and tremolite-carbonate ∓ talc rock. Irregular porphyroblasts of metamorphic olivine are present in the more serpentine-rich rocks. Metamorphosed BIF and amphibolite occur to the west, and mafic schist with semi-pelitic metasediments are present to the east.

Amax completed 1 751 m of diamond drilling in 1974-1975 but the best intersections were of less than 1 m containing 0.7 to 1.1 per cent nickel. Pentlandite, linnaeite, pyrite, chalcopyrite, bornite and rare millerite are reported, with alteration to niccolite, maucherite and gersdorffite in more carbonated zones.

ANTIMONY NICKEL PROSPECT (32°17′15″S, 119°44′05″E)

Antimony Nickel prospect, 9 km northeast of North Ironcap Hill, is located in the Central ultramafic unit in an area devoid of outcrop except for amphibolite and BIF rock fragments. A coarse-grained, partly serpentinized dunite was intersected in 3 diamond drillholes completed by Amax in 1974 and 1976. Irregular disseminations of pentlandite, pyrite, pyrrhotite and chalcopyrite occur as fine- to medium-grained aggregates and coarse blebs in the metadunite. The best intersection averaged 0.61 per cent nickel over a drilled width of 0.78 m.

WEST QUEST PROSPECT (32°15′50″S, 119°46′15″E)

West Quest prospect is 14 km northeast of North Ironcap, and occurs in the Eastern ultramafic unit. Dips are at steep angles to the west or east. A geochemical anomaly of 3 400 ppm nickel and 290 ppm copper encountered in a rotary airblast drillhole was tested by two diamond drillholes in 1975. Massive sulphides in footwall metasediments containing 0.5 to 0.6 per cent nickel over drilled widths of 1 to 5 m were encountered.

MOUNT HOPE PROSPECT (32°10′00″S, 119°47′30″E)

Traced northwards from West Quest prospect the Eastern ultramafic unit thickens into a major lens of metadunite up to 1 100 m thick and some 9 km long at the Mount Hope prospect, 5.5 km east of Mount Holland (Plate 1). A capping of silicified and leached metadunite some 60 m thick is developed; the silicified texture of subsequent igneous olivine pseudomorphs is reminiscent of that at Agnew over the Perseverance ultramafic lens. The fresh rock is similar also, with medium to coarse-grained, little-serpentinized, granular but fractured dunite to olivinite forming the core of the lens, and bladed-textured, cracked olivine/serpentine-talc-carbonate rocks forming an envelope up to 100m thick. Unpublished analyses by the University of Western Australia of 3 olivinites and 4 olivine-talc rocks give average volatile-free magnesia values of 49.4 and 47.7 per cent respectively. Metapyroxenitic rocks are best developed on the western margin of the lens, whereas discontinuous bodies of low-grade disseminated nickel sulphides are found near the eastern margin, suggesting that the lens may have been explaced as a sill (Robinson, 1976). Inclusions of amphibolite and metasediment occur in the lens. The dip is at about 80 degrees to the west.

Ten diamond drillholes were completed by Amax to test the mineralized zone outlined by previous exploration. In 4 drillholes (MHD 5, 7, 9, 22) an average of between 0.65 and 0.75 per cent nickel occurred over drilled widths of 11 to 24 m, the best intersection being 0.75 per cent nickel over 16.9 m in MHD 22. Zones of medium-grade (up to 1.74 per cent nickel) mineralization are irregularly dispersed through the lower grade disseminated sulphides (Robinson, 1976). In the violarite-pyrite zone, which persists to 200 m depth, violarite, pyrite, millerite, polydymite, chalcocite and vaesite are found. Violarite is present to a depth of at least 340 m. The primary sulphide assemblage is pentlandite with lesser pyrrhotite, heazlewoodite, mackinawite, chalcopyrite, cubanite, bornite and millerite. Nickel: copper ratios are generally more than 25. Heazlewoodite is common in an intersection assaying 0.92 per cent nickel over a 9 m drilled width in diamond drillhole MHD 16. Granular and bladed-textured metadunite contain the nickel sulphides.

NEW MORNING DEPOSIT (32°27′05″S, 119°40′50″E)

General

New Morning deposit is 11 km south of North Ironcap, on the west limb of the major north-plunging syncline in the Forrestania region (Fig. 22). A gossan on the basal (western) contact of a silicified ultramafic body was discovered in October 1969. Samples of outcrop and residual material generally contain 0.5 to 1.5 per cent nickel and 500 to 2 000 ppm copper, with maxima of 2.45 per cent nickel and 0.3 per cent copper (Leggo and McKay, 1980). Percussion drilling on gossan targets began in late 1971, and diamond drilling started at the end of the year. The first high-grade intersection was of a 5.20 m drilled width averaging 5.59 per cent nickel in diamond drillhole NMD 31 completed in 1972. Further work lapsed until mid-1975 because Amax concentrated exploration at the discoveries of Cosmic Boy and Digger Rocks. More drilling was then carried out, and, to the end of 1977, a total of 43 diamond drillholes (12 999 m) had been drilled to indicate resources of 569 459 t averaging 2.92 per cent nickel (1 per cent cut-off). Additional inferred resources are 355 500 t averaging 2.80 per cent nickel (McKay, 1978).

Stratigraphy and Structure

The strike is between north and north-northeast and the dip is at 70 to 85 degrees towards the east. McKay's (1978) description of the stratigraphy is summarized in Table 26. Granitoid veins are common in the footwall metasediments and are also found in the New Morning ultramafic unit, where metasomatic reaction zones may be developed at contacts. Tectonic interleaving of footwall metasediment with the base of the ultramafic body occurs locally, and talc-chlorite-biotite reaction zones may develop at the contacts.

The New Morning ultramafic unit forms a 3 km-long lens which is thickest in the south where the mineralization occurs. Other lenses in a similar stratigraphic position are found over a strike length of 11 km southwards from New Morning, and a thin lens to the north at Flying Fox deposit is nearly continuous with the New Morning lens.

Ore distribution and petrology

Nickel sulphides are present (a) as low-grade, patchy disseminations in the central and upper parts of the ultramafic unit; (b) as disseminated (some triangular-textured), matrix to massive and breccia ore in the basal ultramafic unit; and (c) as veins of breccia ore offset into the footwall metasediment. The low-grade internal mineralization is not included in the resource calculation; the better, more continuous intersections average about 1.5 per cent nickel over drilled widths of up to 20 m. Basal and offset nickel sulphides have been encountered in 32 diamond drillholes over a strike length of 880 m, though

TABLE 26. GENERALIZED STRATIGRAPHY AT NEW MORNING DEPOSIT, FORRESTANIA GROUP

Unit	Lithology	Thickness (m)
(7) Distal hangingwall metasediments	Semi-pelitic schist	1 300
(4) Hangingwall magnesian basic rocks	Massive to schistose tremolite-chlorite rocks (east-facing spinifex textures); some serpentine-rich rocks, amphibolite, biotitic metasediment and chert	300-400
(5) Black slate-chert marker		15-50
(4) Hangingwall magnesian basic rocks	As for (6)	80-245
(3) Hangingwall chert	Pyritic, distrupted by intrusion of (2)	6-30
(2) New Morning ultramafic	Partly serpentinized, close packed, green granular metadunite, minor talc, enstatite, chlorite, anthophyllite; top and bottom parts are foliated and are tremolitic with mottled-to-bladed textured metamorphic olivine pseudomorphs. Low grade internal, medium-high grade basal, nickel sulphides	20-170
(1) Footwall metasediments	Pale grey, strongly foliated quartz-muscovite + sillimanite schist, some with garnet; quartzite	300
	Intrusive granitoid rocks	

Data are from McKay (1978)

matrix to massive and breccia ores are mainly restricted to the central and commercially important part of the deposit. North of this central part the disseminated sulphides are thicker and more continuous, but of lower tenor (generally less than 1 per cent nickel). To the south of this central part the basal-zone mineralization is less than 1 m thick. Granitoid intrusions are present in the ore zone in 11 of the 32 drillholes, and supergene alteration affects a quarter of the mineralized intersections. The deposit has not been tested below a vertical depth of 380 m.

In the primary zone, the sulphide mineralogy is dominated by pyrrhotite which is three to five times more abundant than pentlandite. Pyrite is a minor phase, and chalcopyrite is an accessory. Lobate sulphide aggregates are again characteristic, pentlandite in particular being cracked and veined by magnetite in some cases. Though cleaved, pyrrhotite is little deformed in disseminated ore, but may contain kink bands and deformation twins in massive ore. Foliation or mineralogical layering is not developed in the samples inspected. Late carbonate veinlets cut all other textures.

FLYING FOX DEPOSIT (32°25′25″S, 119°41′20″E)

The Flying Fox deposit was discovered during rotary airblast drilling on a grid spacing of 61 m by 7.6 m sited on a narrow, ground-magnetic survey anomaly. Massive, textureless limonite after massive sulphides was intersected in one drillhole, and returned an assay of 0.69 per cent nickel, and 0.24 per cent copper (Leggo and McKay, 1980). There is no outcrop as the area is covered by transported sands derived from granitoid rocks. Mineralization was found in 64 of the 74 diamond drillholes (18 690 m total) and indicated resources are calculated at 530 000 t averaging 4.6 per cent nickel at a 1 per cent cut-off (Docking, 1977).

The stratigraphy at Flying Fox is comparable with that described for the New Morning deposit (Table 26). The ultramafic host at Flying Fox is 2.2 km long, 10 to 50 m thick and dips at 40 degrees east-southeast. Granitoid intrusions with marginal chloritic reaction zones are common in the ultramafic body. Granular textured but foliated (by fracture sets), medium- to coarse-grained green-grey, partly serpentinized metadunite is the chief component of the Flying Fox ultramafic unit. Anthophyllite and talc porphyroblasts are superimposed on parts of the igneous olivine aggregates. Bladed-textured metamorphic olivine is uncommon. A tremolitic zone occurs at or near the top of the ultramafic body in some drillholes. Coarse-grained diopside and carbonate may occur in thin layers or veins (?) near the base of the ultramafic unit; the origin of this assemblage is not understood, but a metasomatic genesis is a possibility.

Massive to brecciated sulphide, with metasedimentary, amphibolitic, chloritic, granitoid and metadunite fragments, is the major ore type, although much of it is altered to supergene violarite and pyrite. Most ore is found at the basal contact of the ultramafic unit in the company of adamellite intrusions. The overlying disseminated sulphide is a few metres thick and most of it averages about 1.3 per cent nickel. Other features are summarized in Table 23.

Lobate sulphide aggregates typify disseminated ore, and pentlandite is cracked, granulated, and may be veined by very fine-grained pyrite. Pyrrhotite is essentially unstrained in disseminated or massive to breccia ore. Fine-scale foliation or mineralogical layering in sulphides is lacking.

BEAUTIFUL SUNDAY PROSPECT (32°21′20″S, 119°40′10″E)

This prospect is immediately southeast of North Ironcap, a prominent hill formed by folded BIF which has weathered to form scree obscuring most of the bedrock geology of the prospect. Drilling has encountered rock types similar to those described from the Flying Fox - New Morning area of which Beautiful Sunday represent a strike extension (Docking, 1978).

The mineralized ultramafic body has an irregular intrusive contact with BIF, chert and metasediment which dip to the north-northeast at 45 to 55 degrees but locally are vertical. Alternating amphibolite, spinifex-textured tremolite-chlorite rock, BIF and metasediments occur to the northeast, and siliceous metasediments are present to the southwest. The ultramafic body consists of a basal, tabular, partly serpentinized, granular textured metadunite 600 m long and 30 to 55 m thick, and an irregular upper appendage of metaperidotite with pyroxenitic margins and a dunitc core (Docking, 1978). Coarse-grained anthophyllite, some retrogressively altered, is superimposed on the olivine aggregates of the tabular metadunite. Quartz-feldspar porphyry veins cut the ultramafic rock and BIF.

Disseminated nickel sulphides are found at or near the base of the tabular metadunite over a strike length of 300 m. Typical intersections in the 9 diamond drillholes completed average 1.2 to 1.5 per cent nickel over drilled widths of 1 to 6 m. The oxidized zone extends to a depth of 70 m, the violarite-pyrite zone is prevalent to 160 m, and alteration of pentlandite to violarite persist to 200 m. In primary material pyrrhotite is dominant, accompanied by pyrite, pentlandite and minor chalcopyrite. Millerite is present as the major nickel sulphide in one drillhole (BSD 3). Pyrrhotite-rich breccia ore (1.5 per cent nickel) occurs at the basal contact in diamond drillholes BSD 3 and 6. Pyrrhotite contains oriented cleavage, kink bands and deformation twins in breccia ore, and weak kink bands in disseminated ore; grain boundaries are irregular and sutured but may be smoother where annealing has occurred. Sulphide aggregates in disseminated ore retain a lobate shape.

REMAINING DEPOSITS IN THE YILGARN BLOCK

RAVENSTHORPE DEPOSITS — GEOLOGY AND MINERALIZATION

The Ravensthorpe area is some 550 km southeast of Perth, and about 115 km south of the Forrestania group of deposits. Archaean supracrustal rocks form narrow, steeply dipping belts on the western and eastern sides of an ovoid granitoid pluton; these belts merge northwards. Regional metamorphism attained amphibolite facies conditions and developed dynamic metamorphic, static igneous or overprint textures. East of Ravensthorpe the eastern belt widens southwards and here Thom and others (1977) recognised a major, southeasterly plunging syncline.

Small nickel sulphide deposits occur in the northeastern limb of this syncline, 10 to 23 km east of Ravensthorpe (Plate 1). These deposits are located, with one exception (B1 prospect), in small lenses of olivine peridotite at the basal contact of a mafic to ultramafic, dominantly volcanic sequence. This sequence is underlain by quartzite or recrystallized chert, meta-arkose and BIF (Thom and others, 1977). Thick, extensive dunitic intrusions in these metasediments have lateritic nickel deposits developed upon them at Bandalup (see Chapter 10).

Explortion was carried out from 1964 to 1974 by PMI who discovered all the deposits described below. This work was reviewed by WMC under the terms of a joint venture concluded in mid-1975. New geological mapping was done, and additional geophysics, geochemical drilling and three diamond drillholes were completed. A report by McConnell and others (1975) gives a useful summary of the geology and nickel exploration.

NUMBER 8 DEPOSIT (33°36′10″S, 120°17′50″E)

Most exploration effort has been concentrated on this deposit, situated 24 km east of Ravensthorpe, 300 m north of the Ravensthorpe-Esperance road near a tributary of Bandalup Creek. A lens of mineralized serpentinized olivine peridotite was drilled by PMI (28 diamond drillholes) and WMC (3 diamond drillholes), on a grid approximately 60 m square. The lens is up to about 100 m thick and is confined to a prominent embayment 500 m long, which occurs at a south-dipping contact between siliceous metasediments to the north and tremolite-chlorite rocks overlain by metabasalt to the south (McConnell and others, 1975). The olivine peridotite forms a small hill of weathered outcrop in which relict textures are visible in oxidized material below the siliceous cap. The oxidized zone persists to a depth of 30 m.

In drillcore, bladed-textured olivine pseudomorphs accompanied by talc alternate with granular, cumulus-textured serpentinite. Talc-carbonated and foliated varieties occur throughout the lens, but are conspicuous near the base, where thin tremolitic ultramafic rocks may be present. A shoot of disseminated sulphides in the basal part of the lens plunges southeast at about 30 degrees and is 360 m long and 90 m wide. Termination of the shoot down-plunge occurs where the dip steepens. Within this shoot is a small body of breccia- to massive-sulphide 120 m long and about 25 m wide in plan projection. Disseminated sulphides contain up to about 2 per cent nickel, and massive sulphides up to 18 per cent. Primary sulphide mineralogy is pentlandite and pyrrhotite with minor pyrite and chalcopyrite. Millerite occurs in some low-grade disseminated sulphides. Indicated resources of sulphide mineralization are 249 900 t averaging 1.95 per cent nickel (4 873 t contained nickel).

NUMBERS 3 AND 5 PROSPECTS (33°35′50″S, 120°14′40″E)

These prospects are 19 km east of Ravensthorpe and 300 m north of the Ravensthorpe-Esperance road, in a regional stratigraphic position which is similar to the Number 8 prospect. The prospects are adjacent to one another in an area of little outcrop. Tremolitic ultramafic rocks, talc-carbonate rock and bladed-textured, serpentinized olivine + talc rocks occur at the base of a thick sequence of metabasalt or amphibolite. Banded chert dipping south forms the immediate footwall of the ultramafic rocks. At Number 5 prospect, the western of the two, only one (RB 5/14) of 21 diamond drillholes completed by PMI intersected mineralization of note. This consisted of a 4.9 m drilled width of pyrrhotite-rich breccia sulphides (up to 2.4 per cent nickel) in contact with the chert and overlain by 2 m of disseminated sulphides in talc-carbonate + serpentine + tremolite rock. Percussion drilling at Number 3 prospect encountered massive pyrite along the basal contact of the ultramafic unit, and one diamond drillhole (RB 3/1) intersected 0.9 m of disseminated sulphides averaging 0.51 per cent nickel in a similar host to the mineralization at Number 5 prospect.

NUMBER 1 DEPOSIT (33°35′10″S, 120°12′50″E).

Number 1 deposit and an extension to the west are located 15.5 km east of Ravensthorpe, and 1.5 km north of the Ravensthorpe-Esperance road, in recently cleared farmland. Ferruginized serpentinite forms a small hill and outcrops of fine-grained lineated quartzite (recrystallized chert) are present on the north side. Dark grey-green, partly foliated, serpentinized olivine peridotite with granular, cumulus, or bladed textures is the major ultramafic type in drillcore. Disseminated to matrix and patchy triangular-textured sulphides occur at or near the base of the serpentinite over drilled widths of a few metres. Veins of breccia sulphides are also present. Pyrrhotite is the dominant primary sulphide phase, with minor pentlandite and accessory chalcopyrite; magnetite may be abundant. Indicated resources have been estimated by P.M.I. at 473 200 t averaging 1.49 per cent nickel (7 051 t contained nickel).

NUMBER 4 DEPOSIT (33°34′35″S, 120°13′10″E).

This deposit resembles Number 1 deposit, except that the mineralization is lower grade. It is located 1.3 km north-northeast of Number 1 deposit, adjacent to an east-northeast-striking dextral fault. The stratigraphic layering still dips southwards, and the ultramafic rocks have a footwall of fine-grained, lineated and folded quartzite. Fine-grained grey-green serpentinized olivine peridotite forms the bulk of ultramafic host; vague, granular, cumulus textures are evident in places. Serpentinized acicular anthophyllite(?) porphyroblasts up to 30 mm long may be present. Fine-grained disseminated sulphides, rarely containing more than 1 per cent nickel are patchily distributed through serpentinite. The possible presence of some 926 000 t of mineralization averaging 0.69 per cent nickel has been inferred by PMI.

NUMBER 4W PROSPECT (33°34′05″S, 120°12′40″E).

This prospect is 1 km northwest of Number 4 deposit and consists of isolated drillhole intersections of fine-grained disseminated sulphides and foliated breccia sulphides. The ultramafic host is a foliated, bladed-textured, serpentinized olivine + talc + carbonate + tremolite rock. In diamond drillhole RB 4W/4B thin breccia sulphides contained 6 to 10 per cent nickel.

NUMBER 11 PROSPECT (33°34′20″S, 120°12′30″E).

Some 500 m south-southwest of Number 4W prospect, minor mineralization was found by PMI in one diamond drillhole in serpentinite intruded by a dolerite dyke at Number 11 prospect. A drilled width of 0.76 m in serpentinite at the dolerite contact averaged 1.14 per cent nickel.

B1 PROSPECT (33°34′10″S, 120°09′20″E).

The B1 prospect is the only nickel sulphide mineralization found at a stratigraphic level above the base of the mafic-ultramafic sequence and on the southwestern limb of the syncline. The prospect is 10 km east of Ravensthorpe and 1.2 km north of the Ravensthorpe-Esperance road, in recently cleared mallee country. Blebs and disseminations of pyrrhotite-dominated sulphides occur in talc-serpentine-carbonate ∓ chlorite ∓ tremolite rocks interlayered with quartzite and BIF. The best intersection was from diamond drillhole B1/10, which averaged 1.09 per cent nickel over a drilled width of 5.03 m.

MAGGIE HAYS PROSPECT (32°14′35″S, 120°30′50″E).

Maggie Hays prospect is 160 km southeast of Southern Cross, in the Lake Johnston area (Gower and Bunting, 1976). A northwest-striking, irregular supracrustal belt about 100 km long contains mafic to ultramafic rocks, felsic, tuffaceous or clastic rocks, chert and BIF which have been subjected to amphibolite facies regional metamorphism. Rock types resemble those described above from the Forrestania region. The east-striking Jimberlana Dyke cuts this belt just north of Lake Johnston.

The prospect is 8 km northwest of Maggie Hays Hill, and 2 km south of where the Jimberlana Dyke cuts the belt. Exploration in the region was conducted by Union Miniere Development & Mining Company in joint venture with Laporte Mining Company from 1966 to 1973, and by Amoco in 1974 and from 1978 onwards. This work outlined a largely concealed olivine-rich ultramafic unit forming a generally conformable intrusion into vertical or steeply northeast-dipping metasediments and BIF. Disseminated nickel sulphides were located in granular serpentinite and talc-magnesite rock during drilling of the eastern contact of the ultramafic unit; this unit varies in its subcrop width from 150 to 400 m. The contact mineralization encountered in 3 diamond drillholes, (Sheppy, 1979) covering a strike length of 350 m, averaged 0.98 per cent nickel over a 6.1 m drilled width (DDH LJ 3), 1.0 per cent nickel over 2.44 m (DDH LJ 6) and 0.57 per cent nickel over 6.86 m (DDH BWA-74-2). In addition disseminated sulphides within the ultramafic body were intersected over a drilled width of 58 m averaging 0.50 per cent nickel (DDH LJ 14). Further exploration is in progress.

CHAPTER 5

Volcanic peridotite-associated deposits

SUMMARY OF GEOLOGY AND MINERALIZATION

DISTRIBUTION

All the important deposits of this type are confined to the Norseman-Wiluna belt, a major geotectonic subdivision of the Yilgarn Block which is described in Chapter 3. Within this belt about 87 per cent of the mineralization (in terms of pre-mining contained nickel resources at 1 per cent nickel cut-off) is restricted to the Kalgoorlie-Norseman area, the remainder being accounted for largely by the Windarra deposits. Furthermore, three-quarters of this 87 per cent is provided by the Kambalda and St Ives groups of deposits. On this basis alone, earlier designations of deposits of this type as "Kambalda-type" are therefore amply justified.

Inspection of Plate 1 suggests that the following geological features are of potential importance in explaining the pre-eminance of the Kalgoorlie-Norseman area as a nickel repository:

1. abundance of volcanic ultramafic rocks of peridotite to olivine peridotite composition;
2. the presence of several, persistent, closely spaced strike faults; and
3. the presence of small, ovoid granitoid bodies occupying plunging anticlinal structures within supracrustal rocks.

The strike faults are regarded as the most important feature in that they are interpreted as reflecting deep-seated and temporally persistent zones of crustal (and possibly upper mantle) weakness, which influenced the distribution of the other two features listed (cf. Barnes and others, 1974; Archibald and others, 1978). Although most deposits within the Kalgoorlie-Norseman areas seem to be within broadly equivalent ultramafic formations, the lack of deposits in presumed equivalent ultramafic formations outside the Kalgoorlie-Norseman areas (Williams, 1976) indicates that stratigraphy alone is not the control. A relationship between the abundance of nickel deposits and the presence of regional metamorphic terrains characterized by amphibolite facies domains and dynamic-style recrystallization was proposed by Binns and others (1976). However, by their own admission such a correlation is not applicable to the Kambalda (and St Ives) deposits.

STRATIGRAPHY

It is now pertinent to examine the nature of the host ultramafic formations. The apparent importance of regional stratigraphy in determining the economic potential of ultramafic formations within a nickeliferous province has been mentioned. This is perhaps best illustrated by the nickel resources of the older Kambalda ultramafic formation (Kambalda, St Ives and Tramways groups of deposits) versus those of the younger Republican-Bluebush ultramafic formation: the contained nickel resources of the older formation are about 110 times greater than those of the younger formation. Intensive exploration of both formations suggests that this difference is of real significance. Both formations are in areas containing features (2) and (3) listed above, therefore it may be fruitful to examine the local stratigraphy of these and other ultramafic formations with the ultimate aim of determining possible ore guides.

In every case, except the Windarra, Scotia, and Carnilya ultramafic formations, the host ultramafic formations are stratigraphically overlain and underlain by basaltic rocks, some of which are pillowed, variolitic or amygdaloidal. Windarra is the most important exception, particularly in respect of the lack of a footwall basaltic formation, which is not the case at Scotia and Carnilya Hill. Hangingwall basalt does occur along strike from Scotia and therefore the possibility of tectonic excision at Scotia should be considered. The upper parts of the Carnilya and Scotia ultramafic formations contain basaltic rocks interlayered with picritic rocks.

The adjacent basaltic formations generally contain 5 to 15 per cent magnesia and are of tholeiitic and komatiitic affinities, though tholeiitic types are commonly predominant, especially in the stratigraphic footwall of the ultramafic formation. Thicknesses of some basaltic formations are listed in Table 27. The main point to emerge is the large combined thickness of these formations in the Kambalda, St Ives and Tramways groups. This suggests that magamtic activity and related thermal activity in the upper mantle were particularly pronounced here, features which also seem to be reflected in the thicknesses of the mineralized ultramafic formation.

Felsic volcanic and volcaniclastic sedimentary rocks generally overlie the hangingwall basalt formation, and at Republican-Bluebush and Scotia similar rocks underlie the footwall basalt formation. There is some evidence that the sedimentary rocks are of shallow-water origin: Golding and Walter (1979) reported evaporite minerals from the Black Flag Beds* at Kalgoorlie, and A.T. Brakel (pers. comm., 1979) has found mudcracks, high-angle scour structures and graded bedding in what is probably the same formation

** Because of long-standing usage, stratigraphic units are referred to as 'Beds' in accordance with the Australian Stratigraphic Code rather than the International Stratigraphic Guide.*

TABLE 27. THICKNESS OF MINERALIZED ULTRAMAFIC UNITS AND FORMATIONS AND OF ASSOCIATED BASALTIC FORMATIONS

Deposit group or deposit name	Mineralized ultramafic formation thickness (m)	Mineralized ultramafic unit		Hangingwall basalt thickness (m)	Footwall basalt thickness (m)
		Max thickness (m)	Mean MgO (wt%)		
Kambalda	150-800	200	ca.40	260-700	>1500
St Ives	100-200	100	ca.40	greater than Kambalda	>500
Tramways	90-480	40	ca.40	greater than St Ives	>500
Republican-Bluebush	150-450	150		50-250	150-300
Widgiemooltha	upper: 60-120) lower: 100-600)	50	ca.40	250	100-450
Mt Edwards*-Spargoville	100-650	60	ca.40*	0-200	100-450(?)
Nepean	40	40	36	50	40-70
Scotia	500-600	45	45(?)	absent	150
Ringlock-East Scotia	30-270	180		50	200
Carnilya Hill	max.630	30	34(?)	absent	>350
Windarra	max.300	25-130	ca.40	200	absent

Notes:
Ultramafic formations are made up of numerous individual units most of which can be regarded as flows.
* Mean MgO content of Mt Edwards unit only is given.

north of Kalgoorlie. This places some constraint on models for the crustal evolution of the Kalgoorlie-Norseman area, particularly those envisaging deep oceanic rifts or grabens.

The typical mafic to ultramafic sequence being described commonly contains one ultramafic formation only. Two or more ultramafic formations occur in the sequence at Widgiemooltha, Nepean, Republican-Bluebush, Ringlock-East Scotia and Windarra, but in most cases nickel mineralization is restricted to one formation. The only exception is the eastern part of the Widgiemooltha group of deposits where two ultramafic units are mineralized (e.g. Dordie Rocks North and Redross deposits). Most mineralized ultramafic formations are between 100 and 800 m in thickness (Table 27). Absolute thickness of the formation does not seem to be of fundamental importance, but the thickness of the mineralized ultramafic unit and/or of that part of the formation containing olivine-rich ultramafic rocks is significant.

The mineralized ultramafic formations comprise many different ultramafic rock types ranging from picrite through peridotite to olivine peridotite in composition, which in many places are ordered in abundance so that the formation declines in overall magnesia content from base to top. Individual units in the formation can be recognized by the presence of chilled contacts, the distribution of spinifex textures, marked compositional or mineralogical changes at unit boundaries, and by the presence of ultramafic breccia or sulphidic metasediment at contacts. In the absence of recognizable igneous textures, geochemical profiles showing systematic changes in magnesia and silicate nickel contents with stratigraphic height may still be diagnostic for unit identification. These units are regarded as lava flows differentiated during emplacement into a lower more magnesian "B zone", consisting of settled olivine phenocrysts and interstitial liquid, and an upper less magnesian "A zone" consisting mainly of chilled residual liquid which crystallized as spinifex-textured picrite and a flow top breccia. Some units have a thin basal margin of fine-grained picrite interpreted as an original chilled margin. Although spinifex-textured flows are the commonest type of unit, more massive flows characterized by polyhedral jointing are also found (cf. Arndt and others, 1979). The A zones of massive flows have finer polyhedral jointing than the B zones, and may be amygdaloidal (e.g. Windarra, Mount Clifford, Scotia). Pyroclastic to volcaniclastic ultramafic units are rare, and are minor components of the formations at Mount Clifford and Scotia.

Nickel mineralization is confined to units of peridotite to olivine peridotite composition, with the bulk of the known nickel resources being found only in units of olivine peridotite composition with an indicated mean magnesia content of about 40 per cent (Table 27). These units are best developed at or near the base of the ultramafic formation. The ultramafic formation as a whole may be divisible into a lower member containing one or more units of peridotite or olivine peridotite composition, and an upper member containing more numerous units of picrite and peridotite composition (e.g. Kambalda, Windarra). In the particularly well-documented Kambalda group of deposits it can be demonstrated that the internal stratigraphy and thickness of the lower and upper members differs locally according to whether the lower member is mineralized or not (Gresham, 1978). The mineralized flow units have a wide range in thickness (Table 27), but they tend to be best mineralized where thickest. Whether mineralized or not the olivine peridotite units have B zones which are generally 5 to 10 times or more thicker than the associated A zones: this is a requirement for the bulk olivine peridotite composition of the units.

Numerous horizons of thin (1—10 m) laminated sulphidic metasedimentary rocks (Fig.93) are commonly found in the ultramafic formation, and less commonly in the adjacent basalts, at boundaries between flow units. Horizons within the ultramafic formation are laterally impersistent, but are generally more numerous in the lower part of the formation. In some cases horizons either within the basaltic formations (e.g. Kapai Slate in Kalgoorlie-Kambalda-St Ives area), or at the contacts of the ultramafic formation (e.g. Black chert marker in Widgiemooltha area), appear to have sufficient lateral persistence to be of use in stratigraphic correlation. The petrology of these metasediments is complex: quartz, albite, various amphiboles, chlorite, micas, carbonates, talc and iron sulphides are present in very variable proportions. Pale coloured cherty rocks, dark-grey to black carbonaceaous slaty rocks, and dark-green, soft chloritic rocks are three types most characteristic. Less common are felsic volcaniclastic or pyroclastic varieties (e.g. Scotia, Spargoville) and amphibole-dominated sulphidic types which may be intergradational with magnetite-bearing, amphibolitic banded iron-formation (BIF) (Windarra). In all types the sulphur appears to be of magmatic origin (Donnelly and others, 1978; Seccombe and others, 1978), and other components are probably of volcanic origin (Groves and others, 1978; Bavinton, 1979). Metasedimentary horizons are generally not in contact with nickel ores at the base of ultramafic formations, but major exceptions are represented by the Windarra and Scotia deposits.

Metamorphosed dyke- or sill-like intrusions of feldspar prophyry of rhyolitic to dacitic composition, and of andesitic to basaltic dolerite are common in most mineralized environments. Several phases of emplacement are indicated by cross-cutting relationships. Chloritic or biotitic metasomatic reaction zones are commonly developed along the margins of intrusions transecting ultramafic rocks.

STRUCTURE

Most deposits are located in the limbs of major, plunging anticlines. The axial planes of the anticlines are vertical or steeply inclined and have a gently curvilinear strike. The long axes of many deposits are parallel to either the anticlinal axes or subsidiary more steeply plunging fold axes which are probably related to the major folds (cf. Hopwood 1976). Strike-slip and reverse or normal dip-slip faults of moderate to high angles are common.

The shape of the basal contact of the ultramafic formation with the underlying footwall basalt is critical in determining the shape of deposits concentrated at the basal contact. The bulk of the nickel resource is contained in such contact deposits. Commonly a local structural depression or embayment in this contact contains the mineralized basal (and in some examples the succeeding few) olivine peridotite unit that either thickens on entering the embayment or is entirely confined by the embayment. The mineralization may occupy the whole embayment (e.g. Juan Main shoot, Kambalda) or only a portion of it (e.g. Scotia deposit). The margins of the embayments are commonly the locus of faulting (e.g. Kambalda), and sulphidic metasedimentary horizons may thin or die out in the same general area. In some deposits it is possible to demonstrate that the amount

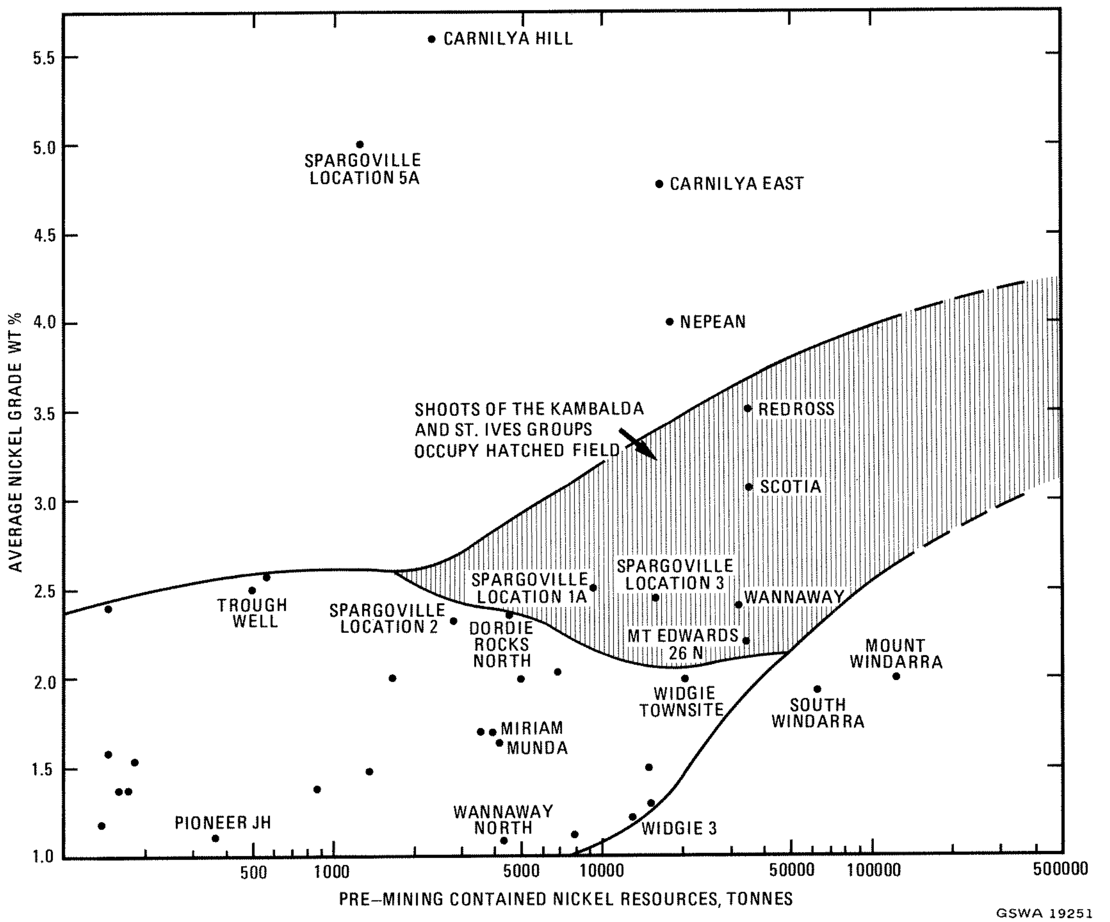

Figure 25. Plot of average nickel grade (weight per cent) versus pre-mining contained nickel resources (tonnes) for volcanic peridotite-associated deposits.

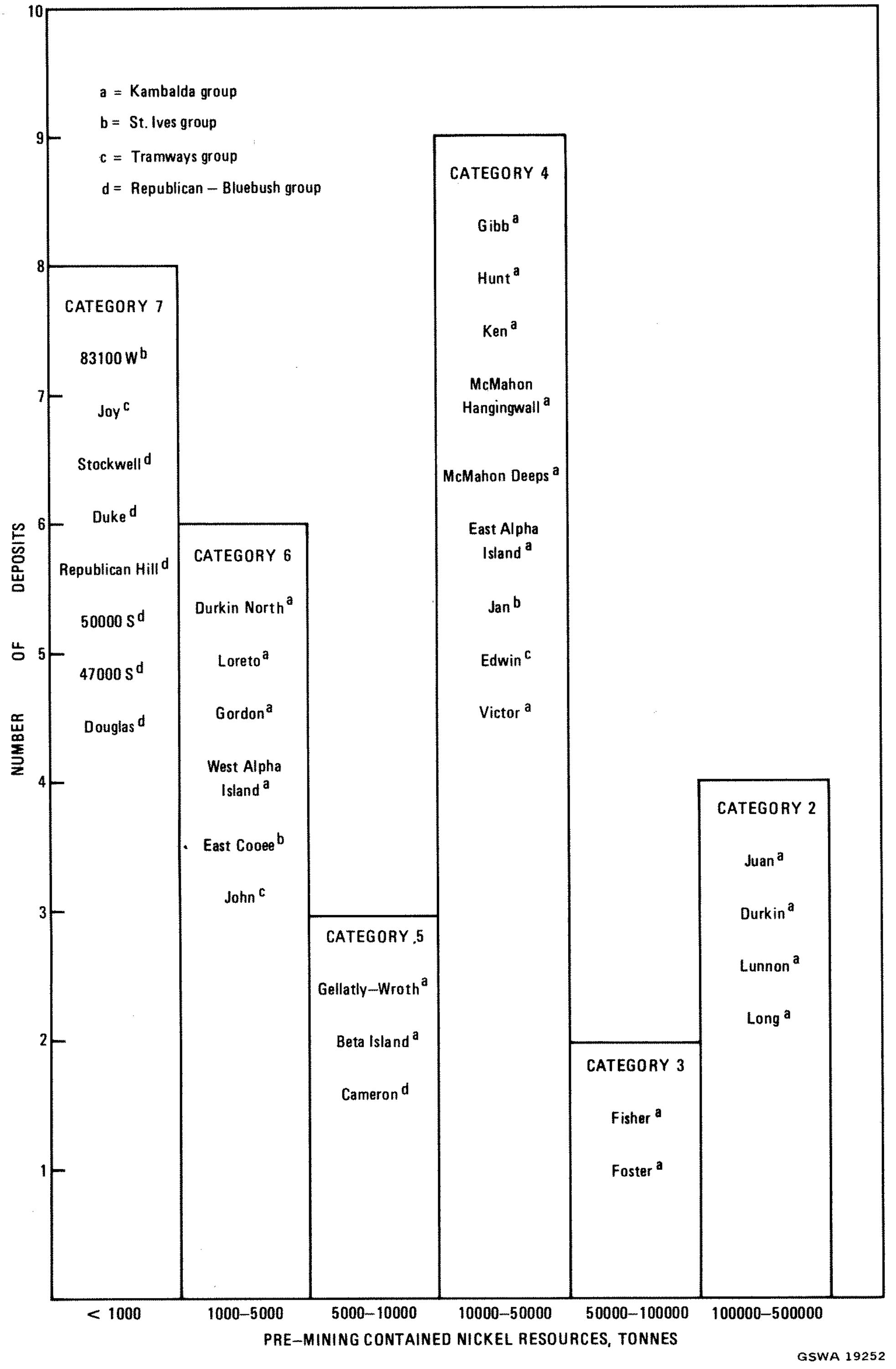

Figure 26. Histogram of the number of deposits in the Kambalda, St Ives, Tramways and Republican-Bluebush groups in defined categories based on pre-mining contained nickel resources (tonnes).

of displacement of the contact between the ultramafic rock and footwall basalt diminishes upwards into the ultramafic formation. More rarely a metasedimentary horizon present on the basal contact outside the embayment, can be traced laterally into the embayment where it occupies a position at the top of the basal ultramafic unit (e.g. Scotia; Ken shoot, Kambalda; 3 shoot, Spargoville Location 3). All these features indicate that the embayments are at least partly syn-depositional topographic depressions in the top surface of the footwall basalt. These depressions have strike and dip dimensions (in their present orientation) of up to several hundred metres and amplitude ("depth") of a few tens of metres. Many embayment at Kambalda have a long axis oriented north-northwest, and appear to be tongue-shaped in plan projection.

MINERALIZATION

Nickel deposits show a wide range in the size of their contained nickel resources but have a small range in their bulk nickel tenor. There is a broad trend towards increasing bulk nickel tenor with increasing deposit size, although there is a large scatter of plots for the small- to medium-sized deposits (Fig. 25). The Windarra deposits have a significantly lower tenor than other large deposits. In any given group of deposits there is commonly a range in individual deposit size (and tenor) with at least two of the size categories as defined in Figure 26 being represented. A deposit may in turn consist of one or more shoots (separate bodies of mineralization) which again show a range in size and tenor. The physical dimensions of shoots in terms of strike length and dip of plunge length, vary from about 100 m x 50 m for category 7 resources through 300 m x 70 m (category 5) to 700 m x 150 m (category 3). The thickness of shoots is approximately inversely proportional to bulk tenor: moderate- to high-tenor (greater than 2 per cent nickel) shoots are typically 1 to 5 m thick, whereas low-tenor shoots (1 to 2 per cent nickel) attain a thickness of 5 to 20 m.

It is estimated that about 90 per cent of the pre-mining contained nickel resource is represented by contact ores present in units at the bases of the ultramafic formations. Hangingwall ores occur in stratigraphically higher units, commonly the first to the third above the basal unit. Some hangingwall ore is present in all groups of deposits, but large individual deposits consisting of more than 90 per cent hangingwall ore are rare: Mount Windarra (category 2) and Jan shoot, St Ives (upper category 4) being the only known examples. Mount Windarra is a special case in that the stratigraphic setting and low tenor of the mineralization is unusual as mentioned above. A small proportion of contact ore may be tectonically displaced into otherwise barren ultramafic or basaltic rocks; this is commonly referred to as offset ore. Where contact and hangingwall ores occur in the same deposit, hangingwall ore is mainly vertically above contact ore if both are restored to the horizontal.

In detail, the distribution of ore within shoots is irregular and complex, being influenced by small faults, folds and flexures which displace or deform the basal ultramafic-basalt contact. Offset ore may be displaced into such faults or along the margins of cross-cutting felsic of mafic dykes.

A typical section through ore from base to top (i.e. an 'ore section') consists of thin massive sulphides of variable thickness, overlain by disseminated to matrix sulphides which are thicker, more persistent and areally more extensive than the massive sulphides. Massive sulphides are commonly thickest (or in some cases are only found) in structurally complex parts of the shoot (such as in fold hinges, adjacent to reverse faults or dykes) and in irregularities in the footwall or hangingwall. Locally, some massive sulphide is restricted to small embayments, pockets or fissures (resembling neptunean dykes rather than tectonic veins) in the top of the footwall basalt which are probably original depressions in the surface of the mafic lava pile (e.g. Durkin and Ken shoots, Kambalda). Deformation was concentrated in the ore section in many shoots because (i) the ultramafic-basalt contact represented a structurally anisotropic plane; and (ii) sulphide-rich ores behaved in a less competent manner compared with their wallrocks. Thus, only in little-deformed environments is it possible to recognize primary small-scale features controlling ore distribution such as those mentioned above. Where deformation has been intense (e.g. Redross, Spargoville, Mount Windarra) common features are (a) breccia sulphides, consisting of deformed rock fragments in a foliated sulphide matrix (Fig. 91A); (b) offset massive sulphide veins; and (c) the displacement or boudinage of cross-cutting felsic or mafic dykes in the ore section. Much of the internal structure and textures of ores, particularly massive sulphides, are the result of metamorphism and deformation (Barrett and others, 1977; Marston and Kay, 1980).

Factors which control the bulk nickel tenor of a deposit are (i) the proportion of massive ore to less sulphidic ores; and (ii) the nickel content of the sulphide assemblages themselves. For most deposits, especially the larger ones, the first factor is the more critical because there is only limited variation in the amount of nickel in 100 per cent sulphide assemblages. For the majority of deposits this figure is between 10 and 20 per cent nickel, the mean bulk values for deposits of the Kambalda and Windarra groups both falling between 14 and 15 per cent. Clearly then the larger deposits contain proportionally more massive ores than the smaller deposits.

The common opaque ore mineralogy is, in order of decreasing abundance: pyrrhotite, pentlandite, pyrite, chalcopyrite, magnetite and chromite, plus accessory iron and nickel arsenides and chromite, plus accessory iron and nickel arsenides in some deposits. Nickel-rich sulphides such as millerite and heazlewoodite are rare, being confined to blebby or low-grade disseminated ore in serpentinite, with the notable exception of massive milleritic ores at Gibb and Otter shoots, Kambalda. Variations in the pyrrhotite:pentlandite ratio are more important in controlling the nickel content of most ores, and may result in this figure ranging from 5 to 20 per cent nickel for massive ore, though a smaller range would be more typical for a single deposit. Bulk Fe:Ni ratios average 3.4 (standard deviation 1.3) and bulk S:Ni ratios average 2.8 (0.7). In some deposits (e.g. Fisher 14H zone, Foster shoot, Mount Edwards 26N, Windarra) the low nickel values may locally relate to an intimate association between nickel ore and iron-sulphide-bearing metasedimentary rock in the footwall.

In contrast the local development of the pentlandite-rich massive ore may be observed where contact ore is offset into the footwall metabasalt or amphibolite (e.g. Redross, Spargoville Location 3). More extensive and systematic developments of high- and low-tenor massive ores are known at Kambalda. Firstly, along the northern and eastern side of the Kambalda dome, contact massive ores in the Juan-Durkin-Gibb/Long-Victor belt of shoots can be arranged into two parallel zones of high versus low nickel tenor. Secondly, at the southern end of the dome massive ores in hangingwall orebodies are commonly found to be higher grade than those in stratigraphically underlying contact orebodies.

Bulk Ni:Cu ratios mostly fall between 7 and 19 (mean 13.6, standard deviation 4), the only exceptions being South Windarra (22), Carnilya East (20-24), Miriam (23) and Bouchers (30). Preferential migration of copper during regional metamorphism is a likely explanation for these anomalies, except that the low copper content at South Windarra may be related to the very magnesian nature of the ultramafic host (see Chapter 3). There is less information on bulk Ni:Co ratios which average 47 (standard deviation 7). In general Ni:Co ratios decline with increasing S:Ni and Fe:Ni ratios. Although the absolute amount of cobalt in nickel ore increases with nickel tenor, the increased cobalt is diluted amongst the much greater amounts of pentlandite (and pyrite in some cases) present in nickel-rich ore. Palladium and, to a lesser extent, iridium and platinum, increase in amount in proportion to nickel tenor (Ross and Keays, 1979).

GENESIS

Several models have been advanced to explain the genesis of volcanic periodotite-associated nickel deposits in Western Australia and other associated terrains, but the consensus favours ore formation from an immiscible Fe-Ni-Cu sulphide liquid of magmatic origin (e.g. Ewers and Hudson, 1972; Naldrett, 1973; Ross and Hopkins, 1975; Groves and others, 1979). This is referred to later as the 'magmatic model'.

Lusk (1976) advanced a volcanic-exhalative model which envisages massive nickel ores as lateral equivalents of the laminated sulphidic metasedimentary horizons, and less sulphidic ores as the product of melting of volcanogenic sulphides by over-riding peridotitic lavas. Many objections to this model are proposed by Groves and others (1976, 1979) and Bavinton (1979): the more cogent points are (i) the stark contrasts between the chemistry and silicate-oxide phase mineralogy of massive ores versus metasediments; and (ii) the fact that very little nickel ore is contiguous with metasediment. This model may have local relevance to a few deposits which are intimately associated with sulphidic metasediments; these deposits are considered in Chapter 7. This model is not discussed further here.

While accepting the fundamental importance of a magmatic model, several authors have referred to the modifying effects of tectono-metamorphic processes (McCall, 1972; Ross, 1974; Groves and others, 1976; Barrett and others, 1977; Green, 1978; Marston and Kay, 1980). These processes and effects are summarized below, and some are described in more detail in Chapter 2, (behaviour during metamorphic processes section):

(i) Metamorphic homogenization: causes sulphides to revert at least partly to monosulphide solid solution *(mss)*; destroys primary layering or inhomogeneities in massive ore.

(ii) Separate deformation of massive ore: may cause physical migration of low-strength massive ore filling fold cores or fractured zones (e.g. breccia sulphides); minute gangue inclusions and spinels are distributed throughout massive ore.

(iii) Pre- or post-metamorphism segregation: results from the deformation of massive ore in a mineralogically layered (i.e. not homogenized) condition, allowing possible preferential segregation of low-strength (e.g. pyrrhotite, chalcopyrite) versus high-strength (e.g. pentlandite, pyrite) minerals; should cause a wide range of Fe:Ni ratios.

(iv) Metamorphic oxidation and element diffusion: oxidation of pyrrhotite or mss during talc-carbonate alteration of the ultramafic host generates either some magnetite and pyrite in massive ores or S-poor Ni-rich minerals in low-grade disseminated ores; stress-induced diffusion of sulphur and copper enriches some ores (in folds, veins, brecciated zones) in pyrite and/or chalcopyrite, and may increase bulk Ni:Cu ratio of massive ore; local diffusion of nickel into contiguous sulphidic metasedimentary rocks; unusually intense, localized oxidation may completely oxidize some massive ores in fractured environments with abundant felsic intrusions (?source of some oxidizing fluids), as exemplified by Gibb shoot.

(v) Metamorphic recrystallization: produces solid-state intergrowth textures between sulphides, oxides and metamorphic silicates and carbonates including triangular-textured ore (Fig.92A); causes deformation and annealing textures in sulphide aggregates (e.g. Fig.94A); develops porphyroblastic pyrite (Fig.89A) and pentlandite; forms currently observed mineralogical layering (Fig.88A) and fine-scale foliation (Fig.94B).

(vi) Upgrading of less sulphidic ores: produces patches of massive ore in matrix or disseminated ore, and disseminated to matrix ore in metasomatic reaction zone material.

Evidence that some of these processes have operated can be found in nearly all deposits; in particular the effects of processes (ii) and (v) are very common.

Secondary modification is therefore mainly physical. Ross and Keays (1979) concluded, on the basis of platinoid data at Kamblada, that there was no evidence to suggest that metamorphism had made important changes in the bulk magmatic composition of the sulphide ores. Examination of the chemistry of the ores and its ultramafic host demonstrates the importance of igneous processes in genesis.

Despite small differences in copper content, which may be the result of processes (iii) and (iv) above and perhaps some magmatic fractionation, massive ores are very similar chemically to associated disseminated ores. Disseminated ores are an integral part of igneous ultramafic hosts with distinctive and very restricted chemistry. The mineralized ultramafic formations also contain zinc-rich chromites which are not common in barren ultramafic formations (Groves and others, 1977), although strong partition of zinc and chromium into the sulphide-oxide melt versus the peridotitic silicate-oxide melt, probably resulted in the ultramafic hosts being depleted in these elements overall. The compositions of the zoned chromites common in nickel ores (Fig.94C) are consistent with exsolution and crystallization from a sulphide-oxide melt (Ewers and others, 1976). The average Ni:Cu ratio (13.6) of the deposit is in agreement with the expected partition of nickel and copper between a sulphide melt and a silicate melt of a composition similar to that of the host ultramafic unit (e.g. Duke and Naldrett, 1978). These features indicate a strong genetic link btween the magmatic processes responsible for producing and fractionating komatiitic magmas and processes resulting in the associated nickel ores.

Variations of the nickel content of the sulphide fraction of ores can be caused by fractionation at various stages in the magmatic process. When dealing with a sulphide-silicate melt system in a magmatic reservoir two critical factors are: (a) the time of separation of the sulphide melt from a peridotitic melt undergoing fractionation (removal) of olivine (Duke and Naldrett, 1978); and (b) the relative proportions of olivine crystals to sulphide melt at this time (Duke, 1979). In general, early separation at high olivine:sulphide ratios (>100) should result in more nickel-rich ores compared with later separation at lower ratios. Other possible causes of variations in nickel tenor of sulphides are as follows:

1. Fractionation of crystallizing sulphide melts: makes separation of relatively copper- and/or nickel-rich liquids from mss possible at high temperatures (Fig.10), and may apply to some massive ores, which should differ markedly in composition from associated disseminated ores.

2. Oxidation of sulphide melts on emplacement: proposed by Woolrich and Giorgetta (1978) as a mechanism to account for high- and low-tenor ores at Kambalda; such a process seems at variance with the supposed submarine reducing environment of volcanism (see later), and with the co-existence of high-tenor pentlandite-pyrite/pyrrhotite and oxidised millerite-pyrite-magnetite ores at Otter and Gibb shoots; however the existence of primary oxygen-rich (not oxidised sulphide melts is a possibility raised by the magnetite-rich pentlandite-pyrrhotite massive ores of Ruth Well and Victor shoot.

Two points on which the several versions of the magmatic model differ are (i) the stage at which massive sulphide melts separated from the host ultramafic unit; and (ii) whether less sulphidic ores formed simultaneously and began solidifying with massive ores. Further discussion is provided by Groves and others (1979). Based on earlier suggestions by Hudson (1973) and Ross and Hopkins (1975), it is proposed that the peridotitic magma (rich in olivine phenocrysts) and immiscible sulphide liquid were both erupted at the same time as a single flow from a subvolcanic reservoir. Because of the high viscosity contrasts and consequently different flow rates (Ross, 1974), the main mass of (low viscosity) sulphide liquid would be emplaced slightly in advance of the (high viscosity) olivine crystal - rich peridotite magma containing sulphide droplets. The sulphide liquid cools rapidly on contact wih seawater, therefore the overlying peridotitic magma comes to rest on partly crystalline massive sulphides. The sulphide droplets in this magma settled to the base during flow thus forming matrix and/or disseminated ores. The lack of matrix ore in some deposits could be a result of either slow emplacement, with time for segregation of most sulphide liquid into a basal massive layer, or of the close packing of olivines settled at the base of thick flows.

The greater abundance of massive ores in larger deposits can be interpreted as purely a volume relationship: the more liquid sulphide droplets that are carried by an erupting magma, then the greater the volume of sulphide liquid that will settle out at the base of the flow as massive sulphide. Higher eruption temperatures would also favour more efficient segregation. It would appear that in general most of the sulphide liquid is expelled from the reservoir when the first flow erupted, as few deposits contain substantial hangingwall ore. However, it should be noted that the first flows in a given area are not necessarily strictly contemporaneous because of the presence of embayments in the top of the footwall basalt.

The volcanic environment into which the sulphidic magmas were emplaced is poorly defined. Pillowed basalts above and below the ultramafic formations, and laminated sulphidic sediments within the ultramafic rocks indicate a submarine environment with reducing conditions. Water depth is unknown but shallow water features are indicated locally in sediments overlying (Kalgoorlie) and underlying (Windarra) ultramafic-mafic sequences. An irregular topography is an important feature of the basaltic surface onto which the sulphidic magmas were erupted. Depressions were important traps for the segregating sulphidic liquids and their attendant peridotitic flows. Sulphidic sediments were then deposited on the elevated surfaces adjacent to the depressions, and in some cases over the top of the solidified mineralized flow. Elsewhere sediment was deposited before the first peridotitic flow was emplaced.

Evidence for the proximity of the volcanic centre(s) or eruptive sites to the mineralized areas is indirect, because possible feeder conduits for the ultramafic flows (cf. Williams, 1979) have not yet been identified in the State. The abundance of pillowed footwall basalt may related to eruptive sites, and interpillow nickel sulphides of primary origin are known at several Kambalda shoots (Gresham, 1978). Gresham described differences in the ultramafic formation at Kambalda in mineralized versus barren areas, some of which appear to relate to proximity of volcanic centres. Flow units show much better internal differentiation, but the internal stratigraphy of the formation is disordered in mineralized areas. He suggested that these features stem respectively from rapid settling of olivine crystals in a low-viscosity magma (presumable hot and near its source), and damming effects at volcanic centres. Thick, phenocryst-rich peridotitic flows would be expected to have viscosities relative to picritic flows, and consequently would probably not flow far from the site of eruption. Ultramafic fragmental rocks and well-differentiated ultramafic flows are prominent at Scotia, and again suggest a volcanic centre. Thick lenses of coarse-grained dunitic rock at or below the base of the volcanic ultramafic formation (e.g. Mount Clifford, Ringlock - East Scotia) may represent the crystalline residuum of komatiitic volcanism trapped in a subvolcanic reservoir.

The common confinement of hangingwall ores to areas more or less coincident in plan projection (when restored to the horizontal) with contact ores, and the loss in relative displacement when faults marginal to ore-bearing embayments are traced upwards, indicate that the initial depressions persisted in time and were probably fault-controlled in some places. Fault control of the eruptive centres seems likely remembering the importance of strike faults in the Kalgoolie-Norseman area. The deposits at Kambalda can be divided on several criteria into two groups trending north-northwest and paralleling local strike faults which may therefore be of genetic importance (Gresham, 1978). Certain facies changes in the sulphidic sediments here also seem to relate to the same trend.

It is contended that the evolution of the upper mantle during the Archaean has important implications for crustal evolution and the metallogenesis of nickel. The restriction of all important volcanic peridotite-associated (and dunite-associated nickel mineralization) to the eastern, and younger, part of the Yilgarn Block, and a corresponding virtual absence in the older Pilbara Block is the basis for this contention. The importance of crustal lineaments has been mentioned earlier in this chapter and in Chapter 3. Archibald and others (1978) and Gee (1979) mentioned the influence of thermal diapirs or plumes in the mantle in initiating such lineaments in a sialic crust and localizing subsequent mafic to ultramafic volcanicity. Weaver and Tarney (1979) suggested that the size of rising mantle diapirs increased during the Archaean because of increased mantle viscosity (in turn caused by a decline in geothermal gradient as a result of the crustal growth). They go on to conclude that late Archaean supracrustal belts should therefore be larger and more linear.

Most late Archaean komatiitic volcanics seem to be of a type which Nesbitt and others (1979) referred to as 'aluminium-undepleted', being characterized by $CaO:Al_2O_3$ ratios of about one, $Al_2O_3:TiO_2$ ratios of about 20 and flat heavy rare earth element (REE) distribution patterns. The mineralized ultramafic formations in the Yilgarn Block are of this type, whereas the essentially barren, presumed older, ultramafic rocks of the Pilbara Block (and the Barberton Mountain Land) have higher $CaO:Al_2O_3$ ratios, lower $Al_2O_3:TiO_2$ and are depleted in aluminium and heavy REE. The aluminium-undepleted ultramafic rocks are, however, depleted in titania and light REE which is consistent with derivation by high proportions of partial melting of a similarly depleted peridotitic mantle source. Weaver and Tarney (1979) pointed out that such a source allows a higher temperature and magnesia content for the erupted komatiitic liquids than an undepleted (pyrolite) mantle source. Depleted mantle is that which has already given rise to basaltic crust similar to that in modern mid-ocean ridge environments, therefore this mantle type probably became more abundant in the Archaean with time. Hence, the apparent greater abundance of olivine-rich ultramafic volcanics (and related nickel deposits) in the late Archaean may find some explanation.

KAMBALDA GROUP

GEOLOGY

GENERAL

The Kambalda nickel deposits occur in the southern part of the Norseman-Wiluna belt in an area characterized by a stratigraphy and structure which strikes north-northwest (Plate 2). Exploration and development of the deposits has been carried out entirely by WMC. An anticlinal zone of dominantly mafic to ultramafic metavolcanic rocks of both tholeiitic and komatiitic affinities which extends from Kalgoorlie to Lake Cowan is bounded by faults and is 6 to 8 km in width (Plate 1, Fig.27). The deposits occur in the eastern part of this zone in association with a complex major structure referred to locally as the Kambalda dome (Ross and Hopkins, 1975), a structure which is essentially a doubly plunging anticline with subordinate folds and faults striking parallel to its axis (Fig.28).

Ross and Hopkins (1975) described the stratigraphy of the rocks in this zone at Kambalda as a comfortable sequence more than 3 km in thickness (Table 28), which shows some similarity with the lower section of the Kalgoorlie succession of Woodall (1965). This sequence is intruded by later felsic to mafic hypabyssal rocks and plutonic granitoids. The mafic to ultramafic rocks are succeeded by felsic metavolcanic, psammitic and pelitic rocks which resemble the Black Flag Beds at Kalgoorlie. The youngest formation is the Merougil Beds (McCall, 1969) composed of polymictic metaconglomerate, metasandstone and metasiltstone. These rocks are disposed in an elongate partly fault-bounded synclinal structure preserved to the west of the mineralized mafic to ultramafic zone, and they appear to rest uncomfortably on older rocks. Regional metamorphism is of upper greenschist to lower amphibolite facies attaining conditions of up to 510°C ± 20°C at 250 MPa ± 100 MPa according to Bavinton (1979). A static-style of recrystallization characterizes the area and primary igneous textures are generally preserved in the mafic to ultramafic rocks (Barrett and others, 1977), resulting in a static igneous texture (Chapter2).

STRATIGRAPHY

The stratigraphy at Kambalda is summarized in Table 28 which is adapted from Gresham (1978). Although much of these data represent a refinement of the study by Ross and Hopkins (1975), which dealt chiefly with Lunnon shoot, the report by Gresham describes a major team project involving the relogging of about 153 000 m of drillcore

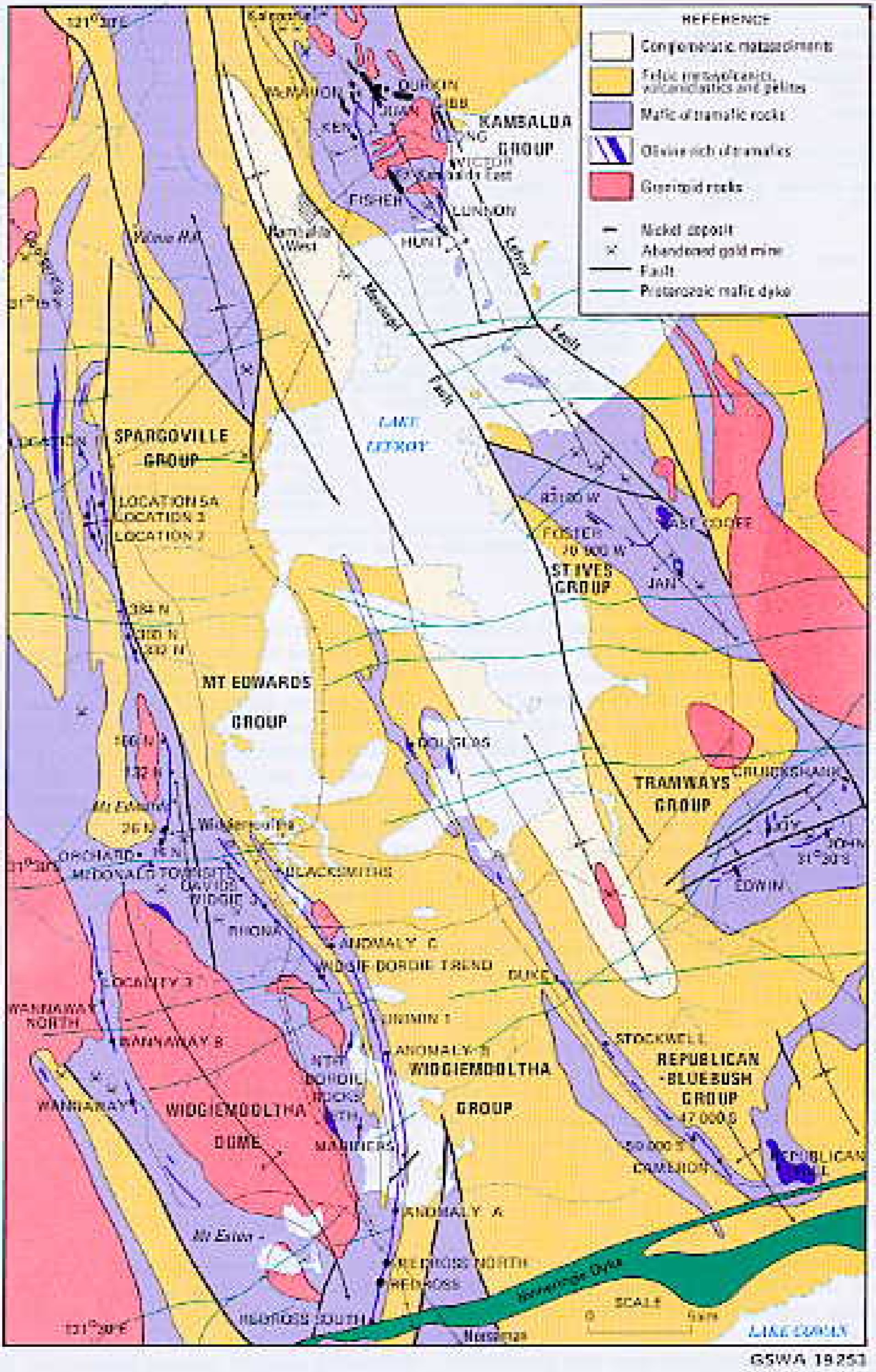

Figure 27. Geological map of the Kambalda-Redross region showing the location of nickel deposits and olivine rich ultramafics.

TABLE 28. STRATIGRAPHY OF THE KAMBALDA AREA

Formation	Equivalent in Kalgoorlie succession	Thickness (m)	Mean and range MgO (wt % vol. free)	Lithology (pre-metamorphism)
Merougil Beds	Not present	>2000	—	Conglomerate, sandstone, siltstone
Un-named formation	Black Flag beds	>500	—	Felsic volcanics, volcaniclastics, sandstone, shale
Hangingwall meta-basalt (upper)	Paringa Basalt	200-600	10(7-15)	Massive and minor pillowed, variolitic basalt, rare agglomerate, rare skeletal amphibole
Metasediment	Kapai Slate	1-10	—	Laminated sulphidic, graphitic, cherty sediment; locally abundant felsic-intermediate sills
Hangingwall meta-basalt (lower)	Devon Consols Basalt	60-100	8(1-10)	Pillowed and variolitic basalt; sharp basal contact
Kambalda ultramafic formation	Hannans Lake Serpentine	150-800	22-45	Picrite to olivine-peridotite flow units, some sulphidic sediment
		BARREN SEQUENCE		*MINERALIZED SEQUENCE*
Upper member		Weakly differentiated and textured, multiple thin (1-10 m) picritic flows overlying similar flows of more peridotitic composition; rare thick (10-30 m) peridotite flows; overall regular decrease in MgO upwards; consistent stratigraphy and simple structure allows good lateral correlation		Well differentiated and textured picritic and peridotitic multiple thin flows; thick peridotitic units (some olivine-peridotite) at base and throughout sequence; some thick picritic flows; complex disordered stratigraphy, no uniform MgO trend; correlation difficult; structural disruption common
Basal member		Thin peridotite or olivine peridotite flows with sulphidic sediment between flows and at basal contact; contact little disturbed structurally		Thick olivine-peridotite flow or flows, generally without sulphidic sediment between flows or at the basal contact in the area above ore; basal flow is 50-200 m thick but has a very thin picritic A zone, overall MgO about 40 per cent; basal flow and ore occupy a trough-like confining structure; structural disruption common
Footwall metabasalt	Not exposed	>1500	8	Mainly massive basalt, subordinate pillowed, agglomeratic and brecciated zones; rare interpillow Fe-Ni-Cu sulphides and sulphidic sediment in upper part

Modified after Gresham (1978)

from 408 diamond drill holes bored around the Kambalda dome. Besides general documentation of the whole mineralized area, this project was designed to provide an assessment of geological features which might, by their presence or absence, be used as guides to nickel ore. Some of these features are summarized in Table 28. The following account is based largely upon Ross and Hopkins (1975), Gresham (1978) and Bavinton (1979).

The key element of the stratigraphy, with respect to nickel mineralization, is the Kambalda ultramafic formation which is comformably underlain and overlain by basaltic formations with average magnesia contents of 8 to 10 per cent. The hangingwall metabasalt is diverse texturally and chemically compared with the footwall metabasalt. Sulphidic siliceous metasedimentary rocks occur throughout the sequence but are most common in the basal member which makes up the lower quarter or so of the ultramafic formation. Nickel deposits are also restricted to the basal member with most mineralization being present at the contact between the basal member and the footwall metabasalt. The descriptions of formations which follow are given in ascending stratigraphic order. Chemical analyses are given in Table 29.

Footwall metabasalt

The footwall metabasalt consists mainly of fine-grained, dark grey to green massive rocks composed of hornblende, plagioclase, chlorite, biotite, quartz and calcite. The plagioclase has a composition ranging from An_0 to An_{65} resulting from the partial preservation of (a) igneous calcic plagioclase; and (b) sodic plagioclase generated at metamorphic temperatures lower than the maximum (Bavinton, 1979). A relict sub-ophitic texture remains. Discontinuous zones of pillowed rock, recrystallized flow-top and tectonic breccia, biotitic, chloritic or hematitic rock, and bleached epidotized or silicified material occur throughout the formation. Quartz veinlets are common (Fig. 89A). Fine- to medium-grained porphyroblastic biotite (or rarely chlorite) is patchily developed, but is partially noticeable at the contact with the overlying ultramafic formation. A cherty sulphidic metasediment occurs discontinuously in the upper 150 m of the footwall metabasalt. Rarely, massive iron-nickel-copper sulphides occur between pillows at or near the top of the metabasalt in proximity to nickel mineralization at the footwall metabasalt-ultramafic contact.

The formation is chemically uniform, and compared with other metabasalts in the sequence it contains more iron and calcium and less copper and chromium (Table 29). The one available rare earth element (REE) pattern shows no preferential enrichment or depletion in any REE compared with chrondritic values (Sun and Nesbitt, 1978). Compared with other metabasalts occuring with volcanic peridotite-associated deposits in the Norseman-Wiluna belt, the footwall meatbasalt at Kambalda is magnesia-rich (Fig. 29).

Kambalda ultramafic formation

In contrast to the underlying footwall metabasalt, this formation is very variable in thickness, petrology and stratigraphy (Table 28, Plate 2). The ultramafic rocks range from meta-picrite to meta-olivine peridotite in composition representing a span of magnesia contents from 22 to 45 per cent (volatile-free), as indicated in Table 29 and Figure 29. The formation appears to be depleted in light REE. All the ultramafic rocks are variously affected by

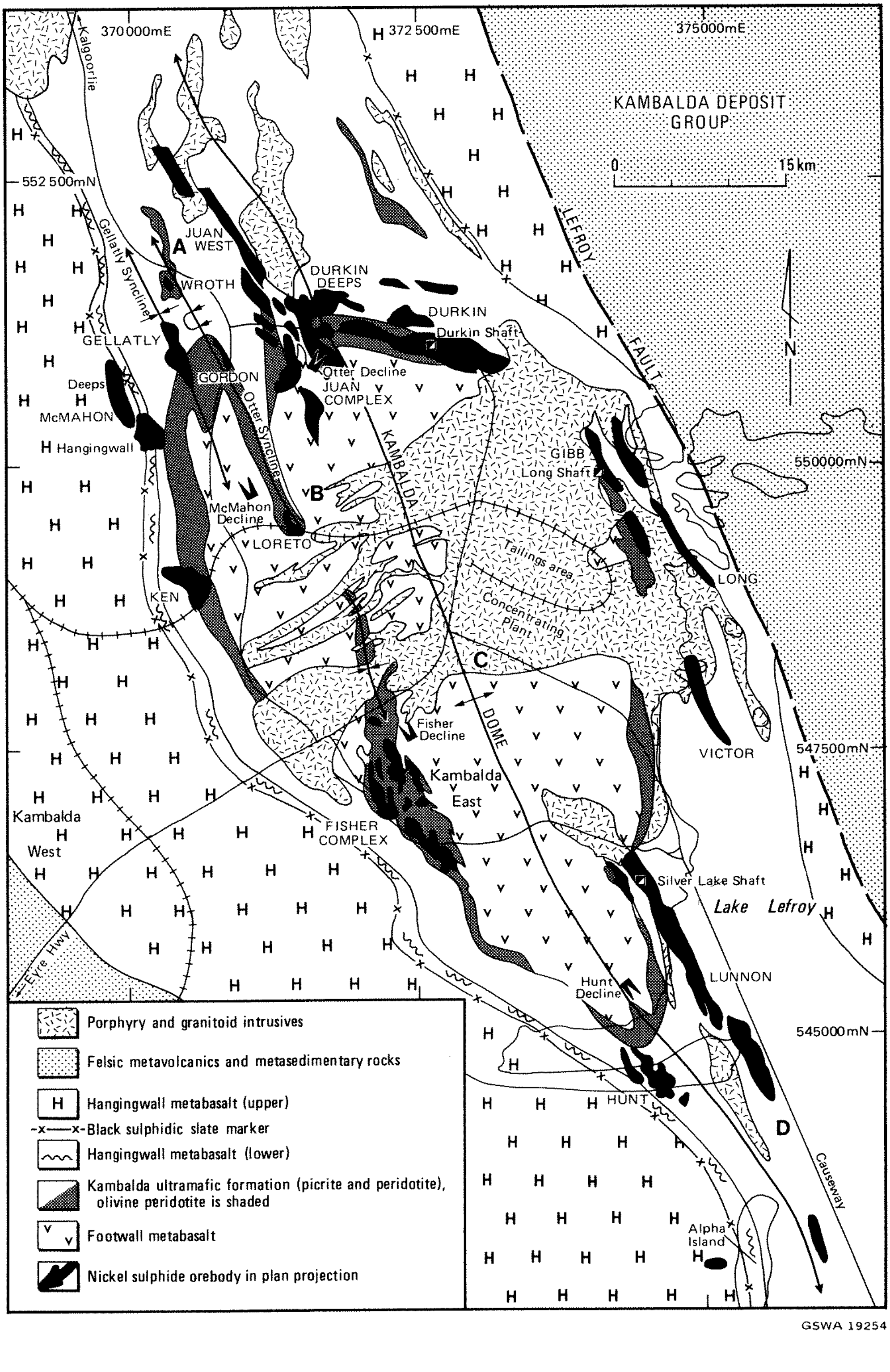

Figure 28. Geological map of the Kambalda group of deposits (from Gresham, 1978).

TABLE 29. CHEMICAL ANALYSES OF ROCKS IN THE KAMBALDA SEQUENCE

Wt % volatile-free	1. Footwall metabasalt	2. Meta-olivine peridotite	3. Meta-olivine peridotite	4. Meta-peridotite	5. Meta-picrite	6. Lower Hanging wall metabasalt	7. Upper Hanging wall metabasalt	8. Siliceous carbonaceous metasediment	9. Mafic chloritic metasediment
SiO_2	51.9	44.0	45.4	47.2	48.1	55.5	53.6	56.0	43.1
TiO_2	0.7	0.1	0.2	0.3	0.3	0.7	0.6	0.5	0.4
Al_2O_3	14.9	3.0	4.1	5.9	8.1	15.9	12.7	12.6	9.3
Fe_2O_3		4.1	3.6	3.9	2.3				
FeO	11.0	4.6	5.4	6.1	8.1	8.8	10.4	13.0	20.8
MnO	0.2	0.1	0.1	0.2	0.2	0.2	0.2	0.1	0.6
MgO	8.2	42.7	37.0	31.0	23.4	6.8	10.7	3.8	9.5
CaO	10.9	0.7	2.7	5.4	8.0	9.1	9.7	4.2	11.4
Na_2O	2.2	—	0.1	0.1	0.1	2.4	1.6	2.9	0.6
K_2O	0.4	—	—	—	0.1	0.4	0.3	2.1	0.7
P_2O_5	0.1	—	—	—	0.1	0.1	0.1	0.1	0.1
C								(0.2)	
S		0.15	0.42	0.16	0.11	0.13	0.09	6.8	9.04
ppm									
As								(39)	
Ba		9		23	10			534	216
Co								117	167
Cu	133	12		31	56	62	76	489	446
Cr	(262)	1573	1094	2394	3010	625	858	181	345
Ni	175	2710	2578	1796	1116	169	221	259	316
Rb	13					9	12	29	34
Sr	141					177	102	137	78
V		48		102	137		192	75	121
Y	19							15	13
Zn	98	56		83	91			1534	1344
Zr	61	11		14	17	64	63	126	89

Notes:
The absence of a figure for Fe_2O_3 indicates total iron was determined as FeO.

1. Average of 16 major element analyses and 195 minor element analyses (Groves and Hudson, 1981). Value for Cr is average of 2 analyses (Ross and Hopkins, 1975).
2. & 3. Average of 12 analyses (Ross and Hopkins, 1975) for each column.
4. Average of 33 analyses (Ross and Hopkins, 1975).
5. Average of 14 analyses (Ross and Hopkins, 1975).
6. Average of 3 bulk estimates (Levy, 1978).
7. Average of 6 major element analyses and 4 minor elements analyses (Bavinton, 1979).
8. Average of 64 major element analyses and 180 minor element analyses (Bavinton, 1979). Values for carbon and arsenic are averages for 12 analyses (Groves and Hudson, 1981).
9. Average of 12 major element analyses and 37 minor element analyses (Bavinton, 1979).

serpentinization and talc-carbonate alteration which have resulted in a complex mineralogy (Table 9). Talc-carbonate alteration followed serpentinization and occurred after the peak of metamorphism (Bavinton, 1979). Relict igneous olivine is very rare and in Victor and Durkin shoots is reported to be Fo_{91-93} in composition, with a nickel content of 2 000 to 4 500 ppm (Bavinton, 1979). Antigorite serpentinites are restricted in distribution to the areas of Durkin shoot, Hunt shoot, Gibbs, Long and Victor shoots, and the Fisher complex (Gresham, 1978). Elsewhere the serpentinized peridotites of the basal member have been carbonated to varying proportions, and in a broad sense the amount of carbonation increases to the west and south of the Kambalda dome (Gesham, 1978). Dolomite is the main carbonate in bulk compositions up to 35 to 36 per cent MgO, whereas magnesite predominates in rocks with more magnesia (Bavinton, 1979). Only minor changes in bulk chemistry have taken place during metamorphic alteration.

The formation consists of numerous individual units which can be recognized by such criteria as: (i) the presence of chilled contacts; (ii) the distribution of spinifex textures; (iii) marked compositional or mineralogical changes at unit boundaries; and (iv) the presence of ultramafic breccia or sulphidic metasediments at contacts (Ross and Hopkins, 1975). Diagrammatic illustrations of these features are given in Figure 30 for a thin, barren, picrite-peridotite unit (Ross and Hopkins, 1975) from the upper member of the formation, and for a thick ore-bearing pictrite-olivine peridotite unit (Marston and Kay, 1980) from the basal member. In accordance with the interpretation of similar units elsewhere (Pyke and others, 1973; Barnes and others, 1974) these units at Kambalda are regarded as lava flows. The flows were differentiated during emplacement into a lower 'B zone' consisting of settled olivine phenocrysts, and interstitial liquid, and an upper 'A zone' consisting mainly of chilled residual liquid which crystallized as spinifex-textured picrite and a flow-top breccia. Some units have a thin basal zone of fine-grained picrite interpreted as an original chilled margin. At Kambalda, Ross and Hopkins (1975) pointed out the great variability of the flow units in terms of (i) their overall thickness; (ii) the thickness of A versus B zones, (iii) the amount of compositional differentiation, and (iv) the extent to which spinifex textures are developed.

Within the ultramafic flow units there is a reasonably regular variation in chemistry reflecting the original ratio of olivine to picritic liquid (Ross, 1974). This is illustrated

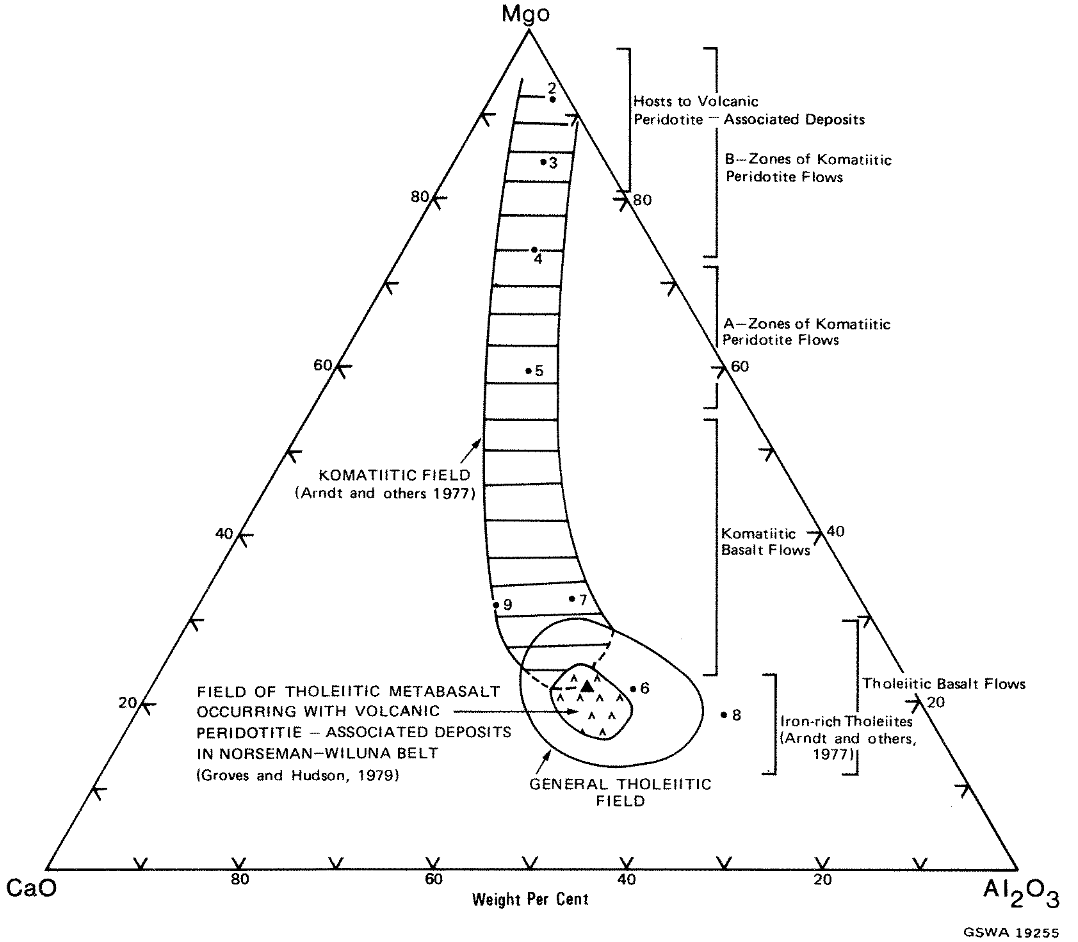

Figure 29. Rocks in the Kambalda sequence (numbered as in Table 29) plotted on an MgO-CaO-Al_2O_3 diagram.

for nickel and magnesia by Figure 30. A reversal to decreasing magnesia content is a feature of the basal part of many units, which probably reflects chilling and differentiation during flow (Ross and Hopkins, 1975). Bavinton (1979) has summarized the partition of elements into the A and B zones of unmineralized flow units as follows:

Elements richer in A zone (picritic liquid):	Ca, Al, Si, Fe, Na, K, Ti, Mn, P, Cr, REE, Y, Nb, Zr, V, Th, U, Ba, Rb, Sr, S, Au, Pd, Cu, Zn, Pb, Co
Elements richer in B zone (olivine-rich):	Mg, Ni, Ir.

Despite all the diversity mentioned there are two consistent features in the flow units which are generally reliable indicators of stratigraphic facing (Ross and Hopkins, 1975). These are: (i) the spinifex textures in the A zone show increasing blade length with increasing distance from the flow top; and (ii) except for the uppermost and lowermost parts, magnesia content increases downwards from the flow top.

The Kambalda ultramafic formation is divisible into two members (Gresham, 1978) which display fundamental differences in character in barren versus mineralized sequences (Table 28, Plate 2). The basal member is comparatively thin, being mainly 25 to 100 m thick where drilled, and is composed dominently of olivine peridotite flow units. The upper member is generally three to seven times thicker than the basal member, and is mainly composed of peridotic and picritic flow units which are only rarely punctuated by interflow sedimentary horizons (Plate 2).

In barren sequences the basal member consists of thin peridotite or olivine peridotite units which are commonly separated by sulphidic sedimentary horizons. The upper member in barren sequences consists of a well-ordered succession of thin peridotitic flows passing upwards into thin more picritic flows; this results in a systematic decrease upwards in the bulk magnesia content of the individual flow units comprising the succession. Plagioclase-bearing picrites, which do not derive their plagioclase from extreme carbonation, are restricted to the top of the member away from nickel deposits.

In mineralized sequences the basal member is commonly thicker (up to 400 m), but sedimentary horizons are generally not present between the flow units (Plate 2).

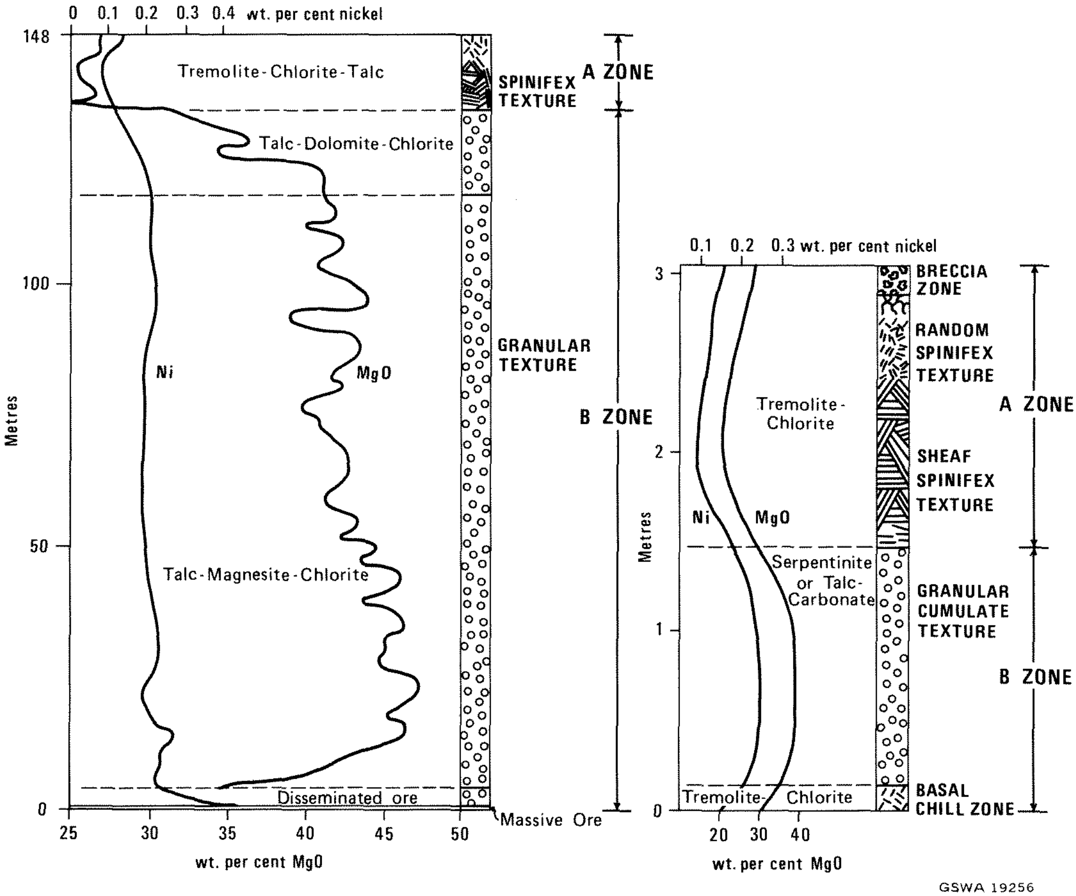

Figure 30. Diagrammatic sections and geochemical profiles through a thick mineralized flow unit differentiated from olivine peridotite to picrite; and a thin barren flow unit differentiated from peridotite to picrite.

The basal unit of the member is particularly thick (up to 200 m), and may in itself constitute the whole of the member. The basal unit is commonly confined to elongated trough-like structures, together with most of the nickel mineralization present on the footwall metabasalt-ultramafic contact (Plate 2). The thick, high-magnesia flow units are commonly characterized by very thin A zones (e.g. Fig. 30), and some contain B zones with chlorite rimming talc-carbonate aggregates — a feature probably pseudomorphic after amygdales (Gresham, 1978). Sulphide blebs may be associated with these aggregates (e.g. Durkin shoot).

The upper member in mineralized sequences lacks the ordered stratigraphy of its counterpart in barren sequences. Picritic and peridotitic flows may be thin (1 to 10 m) or thick (10 to 30 m) and a few olivine peridotite flows may also be present. Most flow units are more distinctly differentiated chemically and texturally (into A and B zones) compared with units in barren sequences. The variety of textures present in the A zone (Fig. 30) is also better developed. The complex internal stratigraphy of the member and the lack of a uniform trend in magnesia content makes correlation of units between drillholes difficult or impossible. Some flow units appear to be structually confined in a fashion comparable with the basal unit of the basal member (e.g. Lunnon shoot).

Metasedimentary rocks

Horizons of metasedimentary rocks 1 to 10 m in thickness are most abundant and best known in the lowermost 100 to 200 m of the Kambalda ultramafic formation where they occur at flow unit boundaries. Bavinton (1979) recognized the following three types, listed in order of decreasing abundance:

(1) pale grey to white 'cherty' rocks (e.g. Fig. 93B) consisting on average (in wt %) of albite (30%), quartz (24%), chlorite (8%), tremolite (7%), micas (8%), and iron sulphides (15%) with no observable carbonaceous material;

(2) dark grey to black, carbonaceous, slaty rocks consisting on average of quartz (30%), albite (26%), tremolite (8%), micas (5%), carbonate (4%), iron sulphides (20%) and carbon (1%) — these rocks are commonest on the west side of the Kambalda dome;

(3) dark green, soft chloritic rocks consisting on average of chlorite (29%), tremolite (12%), quartz (11%), albite (9%), biotite (7%), carbonate (6%), talc (5%) and iron sulphides (18%).

Pyrrhotite and subordinate pyrite are the iron sulphides, which occur in all types of metasediment as layers 5 to 15 mm in thickness, or more rarely as trains of nodules that replace or are interbedded with the layers. Sphalerite and chalcopyrite are minor components of the sulphide fraction.

Types (1) and (2) rocks are similar except for the presence of carbonaceous material, whereas type (3) is distinct both mineralogically and chemically (Table 29, Fig.29). Variability in composition is a feature of all types. A single metasedimentary horizon may consist of several rock types; e.g. a sulphide-rich type (1) assemblage, or a type (3) assemblage, passing down into a type (2) composition, which in turn overlies a type (1) rock that becomes less sulphidic towards the base of the horizon.

The metasediments in general and the specific types have certain patterns of stratigraphic and geographic distribution which are here summarized from Bavinton (1979), and Bavinton and Taylor (1980). Metasediments are almost entirely absent from sections of the ultramafic formation and the ultramafic-metabasalt contacts that are mineralized; this absence typically extends for 100 to 300 m laterally outwards from the edge of the ore shoots (termed a 'void zone' by Bavinton). Metasedimentary horizons tend to thin towards ore shoots. Lateral persistence of individual horizons is commonly very limited (200 to 500 m). The presence of three horizons in the ultramafic is typical; where four to seven units are present these occur one above the other in an area of small extent. Types (1) and (2) metasediments show higher contents of albite, tremolite and total sulphides: (i) on the northern and eastern flanks of the Kambalda dome; and (ii) in horizons within the ultramafic compared with those on the ultramafic-metabasalt contact. Copper, lead, zinc, palladium and REE contents also tend to increase with stratigraphic height above the base of the ultramafic unit.

Changes recorded in metasediments approaching mineralized environments are (a) an increase in the albite:quartz ratio, and (b) a small increase in the titanium and vanadium contents. The few metasediments that are recorded from within the mineralized environment are mostly the type (3) chloritic rocks. Contacts between nickel ore and metasediment are mainly restricted to the edges of ore zones within the ultramafic and ('hangingwall ore') and involve type (3) metasediment and pyrrhotite-rich ore. The four larger ore-bearing areas (Juan Complex - Durkin Deeps - Juan West, Durkin, Gibb-Long-Victor, and Lunnon contact ore), each have less than 1 per cent of their tonnage of ore in close spatial association with metasediment.

Hangingwall metabasalt

This formation is divided into upper and lower members separated by a metasedimentary horizon consisting of well-bedded black slate with variable pyrrhotite and pyrite contents. This horizon is persistent and is commonly intruded by acid to intermediate sills. The contact between the hangingwall metabasalt and the underlying Kambalda ultramafic formation is sharp, being marked by a change in magnesia content from about 10 per cent to more than 20 per cent.

The lower hangingwall metabasalt consists of pale, felsic sections, commonly less than 1 m thick, which alternate with dark green, massive chloritic metabasalt, and thereby account for the wide range of magnesia content (1 to 10 per cent). The felsic sections are pillowed and variolitic. The pillows commonly have a quartz-plagioclase core surrounded by a margin of coalesced felsic ocelli with isolated ocelli present in the more mafic pillow margins. Ross and Hopkins (1975) suggested that the contrasting chemistry of the mafic and felsic sections might be explained by fractionation due to liquid immiscibility as proposed by Ferguson and Currie (1972) for metabasalts elsewhere.

The upper hangingwall metabasalt is made up of fine- to medium-grained, grey-green metabasalt with a few pillowed and variolitic sections. The upper member is far more uniform and several times thicker than the lower member. The bulk composition of the upper member is more magnesian that the lower member (Table 29, Fig. 29). The formation as a whole is similar in chemistry to the footwall metabasalt, the main distinctions being higher silica and chromium contents, and lower iron and copper contents in the hangingwall metabasalt (Table 29). Slight enrichment in light REE is another feature of the hangingwall metabasalt not shared by the footwall metabasalt (Bavinton, 1979).

Intrusive rocks

Much of the core of the Kambalda dome is formed by medium- to coarse-grained porphyritic granite with a high Na:K ratio of about 2.2. The phenocrysts are pink K-feldspar and white oligoclase. Peripheral to this intrusion, and present in every mineralized area, are abundant dykes and sills of sodic rhyolite porphyry of very similar mineralogy (quartz-oligoclase-biotite/chlorite) and composition to the porphyritic granite (Ross and Hopkins, 1975). Less common are porphyry intrusions of dacitic composition. Altered mafic intrusives of basaltic to andesitic composition appear to be rare, and at Durkin shoot they are cut by the felsic intrusives.

Although the intrusive rocks transgress the major structures, several are themselves displaced by small faults and shears which are parallel to the layering in the stratigraphy. The felsic intrusives in particular are fringed by envelopes of biotite or chlorite which seem to have developed by metasomatic reaction during regional metamorphism.

STRUCTURE

The major structure is the Kambalda dome which is an asymmetrical doubly-plunging inclined anticline with an axial surface striking north-northwest and dipping steeply westwards. The axis of the anticline is gently curvilinear and it plunges to the north at about 35°, and to the south at about 10°. Dips on the east limb are generally in the range 40 to 70°, whereas those on the west limb are from 20 to 55 ° (Plate 2). The major embayments in the footwall metabasalt-ultramafic contact on the western limb of the dome are caused by two plunging inclined synclines named the Otter syncline in the north and the Fisher syncline in the south (Fig. 28 and Plate 2). The axial surfaces of these folds dip moderately westwards. Both folds are disrupted by numerous strike faults, particularly high-angle reverse faults, and felsic intrusives all of which post-date the main folding.

The orientation of most ore shoots and their confining structures is parallel to the strike and plunge of the major folds, and the strike of most faults. Durkin shoot, which strikes at 286°, is the major exception in terms of being parallel to major folds, though it is dislocated by many reverse faults which lie parallel to the strike of the footwall metabasalt-ultramafic contact. The confining structures of ore shoots are commonly high-angle reverse faults dipping steeply east or west, with apparent dip-slip movement of up to nearly 300 m, though less than 100 m would be more common (Plate 2). It is probable in some places (e.g. Juan Main and Gellatly shoots) that fold structures resembling box-shaped synclines were the confining structures, which underwent later modification by faulting in the marginal positions (e.g. Marston and Kay, 1980). However, a further complication is the likelihood that original, possibly syn-depositionally fault-controlled, depressions existed in the top surface of the footwall basalt and thereby influenced the emplaced position of nickel deposits at the base of the overlying ultramafic flow. In many examples the amount of displacement apparent on the basalt-ultramafic contact in faults forming confining structures to ore diminishes upwrds into the ultramafic formation, and may not be detectable at all in the hangingwall metabasalt (Plate 2).

The outline of individual ore bodies, of which there are more than 300, is mainly controlled by faults and to a lesser extent by mesoscopic folds. Curving fault planes are common, and the dips of fault planes vary from vertical to horizontal. Low- to high-angle reverse faults with dip slip, oblique slip, or strike slip movements are common. Small-scale displacements along the footwall metabasalt-ultramafic contact are also common. Several generations of faulting are recognizable but structural knowledge is insufficient for proper classification, and each mineralized environment seems to have a somewhat different tectonic history. At Lunnon and Gibb shoots, for example, early low-angle reverse faults are cut by later high-angle reverse faults. However, low-angle to horizontal reverse faults at Durkin Deeps shoot appear to have developed penecontemporaneously with a major high-angle reverse dip-slip and sinistral strike-slip fault known as the Juan Fault. This fault has developed in the axial region of the Kambalda dome, and it separates the west-dipping ore shoots of Juan complex and Juan West from the north-dipping shoots of Durkin and Durkin Deeps (Plate 2). The development of Juan Fault followed the folding of the metabasalt-ultramafic contact and associated nickel orebodies.

The tectonic evolution of the Kambalda region is little understood but important elements in chronological order are: (i) partly fault-bounded depressions developed syn-depositionally in the top surface of footwall basalt; (ii) major folding took place along north-northwest axes; (iii) low- and high-angle reverse faulting developed in an continuing compressional strain regime; (iv) fracturing and the emplacement of mafic to felsic intrusions occurred in a tensional strain regime; and (v) minor faulting locally displaces these intrusives.

MINERALIZATION

GENERAL

Nickel mineralization occurs at different stratigraphic levels in the Kambalda ultramafic formation. According to Gresham (1978), more than 86 per cent of the pre-mining nickel metal reserve occurs in ribbon-like deposits at the contact between the footwall metabasalt and the base of the unit — this mineralization is referred to as *contact ore*. A small proportion of contact ore has been tectonically displaced into ultramafic rocks or the metabasalt, and is referred to as *offset ore*. Typical contact ore has a layer of matrix or disseminated ore, up to 2 m thick, overlying a thinner and less continuous layer of massive sulphides, which rests directly on the footwall metabasalt. The remainder occurs as *hangingwall* ore at higher stratigraphic levels within the ultramafic unit, but commonly it is at the base of the first or second flow unit above the basal unit. It shows the vertical zonation of ore types as for contact ore, and it is in close spatial association with contact ore, being commonly vertically above it (Plate 2). Rarely hangingwall ore occurs as blebs, disseminations and irregular zones within (i.e. not as contacts between) the flow units of the basal member — this will be referred to as *blebby ore*.

The collective term *shoot* includes all contact, hangingwall and offset ores forming subshoots within a particular spatially-associated group. Sixteen such shoots are defined on Figure 28, of which two shoots, consisting of a large number of structurally complicated subshoots, are referred to as complexes (Fischer and Juan). Mining of these shoots currently follows the scheme set out below. The percentage contribution of each mine to the 1977-1978 nickel ore production is indicated in parentheses. Some 10 per cent of the total is contributed by Jan and Edwin mines, which are outside the Kambalda Group. The scheme is:

(i) Juan complex, Juan West, Durkin Deeps are mined via the Otter-Juan decline and the Juan shaft (30 per cent);

TABLE 30. SIZE AND QUALITY FEATURES OF THE ORE SHOOTS OF THE KAMBALDA, ST IVES AND TRAMWAYS GROUPS

Ore shoot(s)	Size cat'gry (a)	ppm As	ppm Zn	Per cent of ore tonnage in hanging-wall ores	Per cent of ore associated with meta-sediment
1. Juan Complex-Durkin Deeps	2	<20	<50	<3	0
2. Lunnon	2	<20	92	53	ca.1.0
3. Gibb-Long-Victor	2	23	102	3	0
4. Durkin	2	<20	82	<3	0.2
5. Fisher	3	62	123	43	5
6. Hunt	4	56	139	36	3
7. McMahon Hangingwall	4	154	183	100	>50
8. Ken	4	131	105	6	3-5
9. Gellatly-Wroth	5	36	96	41	1.5
10. Foster } St Ives group	3	<20	<50	11	ca.10
11. Jan } St Ives group	4	51	155	91	3-8
12. Edwin (Tramways group)	4	30	250	35	3-5

Notes:
a. Size category refers to Figure 26.

Data taken from Bavinton (1979).

Arsenic and zinc contents represent averages of at least eight months' production of ore except for Foster shoot.

TABLE 31. AVERAGE CHEMISTRY OF THE ORE SHOOTS AT KAMBALDA

Weight per cent or ppb*	Juan A	Juan B	Lunnon A	Lunnon B	Durkin A	Durkin B	Fisher A	Fisher B	Hunt A	Hunt B	McMahon A	McMahon B	Ken A	Ken B	Gellatly A	Gellatly B
Ni	3.73	*14.1*	2.40	*12.1*	3.33	*17.2*	1.86	*13.7*	3.25	*10.7*	2.28	*12.0*	3.55	*15.0*	2.56	*8.8*
Cu	0.25	0.95	0.20	1.02	0.24	1.24	0.15	1.14	0.27	0.89	0.20	1.05	0.28	1.19	0.22	0.75
Co	0.08	0.29	0.06	0.30	0.06	0.32	0.05	0.34	0.07	0.23	0.06	0.31	0.08	0.33	0.06	0.20
Fe		46.7		47.8		43.9		46.6		52.5		45.9		39.1		58.0
S	10.07	38.0	7.73	38.8	7.23	37.3	5.20	38.2	10.85	35.7	7.75	40.7	10.49	44.4	9.4	32.2
Pt* 1.	347	1339	284	1445	422	2277	240	1797			267	1402	277	1169		
Pd* 2.	491	1894	318	1615	563	3041	295	2213			312	1636	458	1937		
Au*3.	348	1341	363	1846	312	1686	340	2550			356	1869	273	1153		
Total 1+2+3		4574		4906		7004		6560				4907		4259		
Ni:Cu		14.8		11.7		13.9		12.1		12.0		11.4		12.6		11.6
Ni:Co		48		40		53		40		46		38		46		43
S:Ni		2.7		3.2		2.2		2.8		3.3		3.4		3.0		3.7
Fe:Ni		3.3		4.0		2.6		3.4		4.9		3.8		2.6		6.7

Notes:

1. Column A shows mean values in weight per cent of composite samples of mined ore (Ross and Keays, 1979)
2. *Column B represents data in column A recalculated to 100 per cent sulphides.*
3. Data for Hunt and Gellatly shoots are typical assays of mined ore (Woolrich and Giorgetta, 1978)

(ii) Durkin shoot and Gibb shoot ore is extracted through Durkin shaft (11 per cent);

(iii) Lunnon shoot is mined via Silver Lake shaft (26 per cent);

(iv) Hunt shoot is mined from the Hunt decline (14 per cent);

(v) Ken, McMahon, Gellatly and Wroth shoots are mined via the McMahon decline (9 per cent).

The Fisher complex, formerly mined from the Fisher decline, was on a care and maintenance basis in 1977-78, and was reopened in 1979. Victor, Gordon and Loreto shoots remain undeveloped. Mining of Long shoot from Long shaft began in late 1979.

The ore shoots are graded by the amount of nickel metal in the pre-mining ore reserve (Figure 26 and Table 30), and features of quality which are important in terms of the economics of mining, concentrating and marketing are also shown (Bavinton, 1979). Arsenic and zinc are the chief elements in the ore which may be present in amounts deleterious to the market value of the ore. Hangingwall ore is commonly more costly to mine and treat than contact ore mainly because of the absence of a well-defined and mechanically strong footwall, and a greater abundance of disseminated sulphides. Nickel ores spatially associated with the sulphidic metasediments are also costly to mine and treat because of bad ground conditions, and contamination by the metasediments which are rich in barren iron sulphides and deleterious elements. Several hangingwall ores are associated with metasediments (e.g. McMahon).

The composition of the sulphide fraction of the ores varies between shoots and also between subshoots within one particular shoot (Woolrich and Giorgetta, 1978; Ross and Keays, 1979). The bulk and sulphide fraction compositions of composite samples of mined ore from the various shoots are shown in Table 31. Sampling at this scale shows that Ni:Cu ratios fall within a narrow range of 11.4 to 14.8, S:Ni ratios vary from 2.2 to 3.7, and Fe:Ni ratios range from 2.6 to 6.7. The mean tenor in terms of 100 per cent sulphides varies from 8.7 per cent (high S:Ni and Fe:Ni) to 17.2 per cent (low S:Ni and Fe:Ni). Sampling of subshoots reveals a much greater variation in composition (Table 32), which is largely a function of pyrrhotite:pentlandite ratios, although the very nickel-rich ore of Otter and Gibb shoots contains millerite. The common mineralogy of ore is monoclinic pyrrhotite and pentlandite with pyrite forming less than 10 per cent total opaques, chalcopyrite less than 2 per cent, and magnetite and ferrochromite less than 1 per cent (Ross and Hopkins, 1975).

In general terms the shoots with the largest content of nickel, and the least amount of hangingwall ore and ore associated with metasediment, occur on the eastern limb and at the northern end of the Kambalda dome. This constitutes the Juan-Durkin-Gibb/Long-Victor belt of orebodies. The high-tenor nickel ores are restricted to the same belt, but by reconstructing the original disposition of contact ore (Gresham, 1978; Marston and Kay, 1980), it appears that nickel-rich ores (Table 32) form a semi-continuous zone from Juan, through Durkin and Gibb, to Victor shoot. A parallel zone further from the core of the dome includes the low-tenor ores of Juan and Long shoots. It seems unlikely that the Lunnon shoot - Alpha Island mineralization is an extension of the belt of orebodies referred to above (Gresham, 1978), even though it occurs

TABLE 32. NICKEL CONTENT OF SOME MASSIVE SULPHIDE ORES AT KAMBALDA

A. LOW-TENOR ORES			
Juan West B, Deeps F		Fisher G Zone	7-9
Juan B, Juan Main		Fisher 14H*	3-7
and Durkin Deeps	11-13	Hunt	10
Juan Main Shear	10-14	Hunt*	11-12
Juan West Leg Roll	10-12	Lunnon	9
Long	ca.13	East Alpha Island	7.5
Gellatly	10-12	Ken	8-19
Wroth*	7-8	McMahon Hangingwall*	7-12
McMahon Deeps	5-20	West Alpha Island*	7-9
Fisher, Southern Ore Belt	8-11	West Alpha Island	4-7
		Beta Island*	5-11
B. HIGH-TENOR ORES			
Juan West A	22-28	Durkin	16
Juan Horst	18-26	Gibb	12-40
Juan Banana	18-26	Victor	ca.17
Juan East	16	Lunnon A & F*	17
Otter	17-40	East Alpha Island*	14-19
		Beta Island	4-24

Notes:

1. *Figures are weight per cent nickel in total rock.*
2. • denotes hangingwall ore.

on the east flank of the dome. This mineralization contains a large proportion of hangingwall ore, which increases when traced southwards. All contact ore is low tenor and the hangingwall ore is typically high tenor (Table 32).

All the shoots on the west limb of the Kambalda dome are comparatively small and have high components of hangingwall ore much of which also has a close association with metasediment (Table 30). Additionally, these shoots have relatively high contents of deleterious elements. High-tenor ore is rare (Ken shoot).

Accordingly, the Kambalda group can be divided into eastern and western subgroups defined by a north-northwest-trending line joining points A, B, C and D on Figure 28. Large orebodies with little or no hangingwall ore or metasediment-associated ore, and low contents of deleterious elements characterize the eastern subgroup. Small orebodies with much hangingwall ore and moderate contents of deleterious elements characterize the western subgroup. Lunnon shoot is placed on the boundary between the two subgroups as it demonstrates features characteristic of both. Carbonaceous, slaty metasediments are commoner in the western area, and non-chloritic metasediments have more albite, tremolite and total sulphide in the eastern area. Thus it appears that strike-oriented elements may have had a fundamental control on the composition of the sulphide-rich rocks of the Kambalda ultramafic formation. Gresham (1978) suggested that the Lefroy Fault may have exerted some primary control over magma emplacements and ore distribution.

COBALT AND PRECIOUS METALS

On an annual basis about 150 to 200 t of cobalt, 200 to 300 kg each of palladium and silver, and 50 to 100 kg each of platinum and gold are won as a by-product of nickel mining (Table 1). Most of this production currently originates from Kambalda ore. Pentlandite accounts for the bulk of the cobalt contained in nickel ore, with cobalt contents being in the range of 0.1 to 0.8 atomic per cent. Thus the more nickel-rich ores are generally also richer in cobalt. Pyrrhotite generally contains less than 0.15 atomic per cent cobalt. The cobalt content of pyrite varies according to the type of ore. Values of up to 2.5 per cent cobalt are known, though a range of 0.1 to 1.0 per cent is more typical.

Palladium is principally found in pentlandite (1 000 to 4 000 ppb) with commonly less than 1 000 ppb present in each of the minerals pyrite and pyrrhotite (Woolrich and Giorgetta, 1978). Pyrite and chalcopyrite are the main hosts of gold. Iridium is more or less equally distributed between all sulphide phases, but appears to be enriched in massive ore compared with matrix ore (Ross and Keays, 1979). Sulphide stringers in the footwall or hangingwall may be enriched in palladium and gold, because of the common concentration of chalcopyrite and pentlandite into these sites.

Durkin shoot appears to contain anomalously high amounts of palladium. Fisher, Hunt, McMahon and Lunnon shoots have high gold contents which may in part relate to the presence of hangingwall ore associated with metasediments. The metasediments at Kambalda are known to have anomalously high contents of gold (Bavinton and Keays, 1978).

JUAN COMPLEX, JUAN WEST AND DURKIN DEEPS SHOOTS (31°09′35″S; 121°38′30″E

Introduction

This group of shoots occurs at the northern end of the Kambalda dome (Fig. 28). All the mineralization is blind with the exception of Otter shoot which forms small gossans after massive and disseminated sulphides. The gossans were discovered during the initial geological and soil geochemical surveys in 1965-1966. A sample of gossan after massive sulphide assayed by Travis and others (1976) contained 10.4 per cent nickel, 1.05 per cent copper, 3 580 ppb palladium and 1 930 ppb iridium. Gaspeite occurs in irregular pale to apple green veinlets up to 8 cm thick in the near surface and gossanous portions of Otter shoot.

The shoots are exploited by the Otter-Juan mine which consists of the Otter-Juan decline system and the Juan shaft. The shoots contain a quarter of the geological ore reserve of the Kambalda group (Table 30), and the mine accounts for about one third of annual nickel production. In 1977-1978 production of nickel ore was some 28 000 t per four week period. Diesel-powered trackless equipment is used throughout the mine. In order to reduce haulage distances along the Juan decline (now over 4 km long), a 2.4 m diameter raise borehole was equipped as a shaft (Juan shaft) in mid-1976 to handle broken material from the lower levels of the mine (e.g. Durkin Deeps and Juan West). Before hoisting, the rock is crushed at a crusher station between the 9 and 10 levels. Mining is carried out by slot or cut and fill stoping methods using hydraulically placed sand fill.

Juan Main is the largest and thickest continuous subshoot and, until 1976, it accounted for more than half the annual nickel production of the mine. Production from Durkin Deeps, Juan Banana, Juan Horst, Juan B, and recently Juan West has in turn increased, with the Juan West shoot projected to be the mainstay of output in the mid-1980s. The total pre-mining reserves of the shoots in the group are in Category 2 (Fig. 26), and are probably the largest of any shoot or shoot complex at Kambalda - St Ives.

Stratigraphy

In mineralized areas the basal unit of the Kambalda ultramafic formation commonly equates with the basal member and is 50 to 150 m thick. In other words, one thick flow of meta-olivine peridotite makes up the entire basal member. Thicknesses in excess of 200 m are found in the Otter-Banana area. The upper member has a disordered internal stratigraphy in mineralized areas, but a good development of flow units is reported from the northern part of the upper member overlying Juan West B. Metasedimentary horizons occur on the footwall metabasalt-ultramafic contact and within the ultramafic member, where nickel sulphides are absent.

Where intersected by drillhole KD8159 in the centre of the Juan Main subshoot, the basal unit has a drilled thickness of 178 m (excluding massive ore) and averages 40.7 weight per cent magnesia (Bavinton and Scott, 1975). The A zone is 13 m thick and averages 26.2 per cent magnesia, and the B zone is 160 m thick (excluding ore) and averages 42.7 per cent magnesia. In general, the meta-olivine peridotites of the B zones of the basal unit consist of granular-textured talc-magnesite + chlorite + dolomite with prominent carbonate porphyroblasts in the lowest 3 to 5 m and in disseminated ore. East of the Juan Fault, B zone rocks contain minor amounts of serpentine in places, and some antigorite serpentinite occurs in the Otter shoot.

The footwall metabasalt consists mainly of fine-grained, dark grey-green massive rocks. Locally, these are traversed by quartz veinlets or are paler because of epidotic alteration or silicification. Pillowed zones have been noted in several parts of the mine and, rarely, massive iron-nickel sulphides occur between pillows (e.g. Juan B).

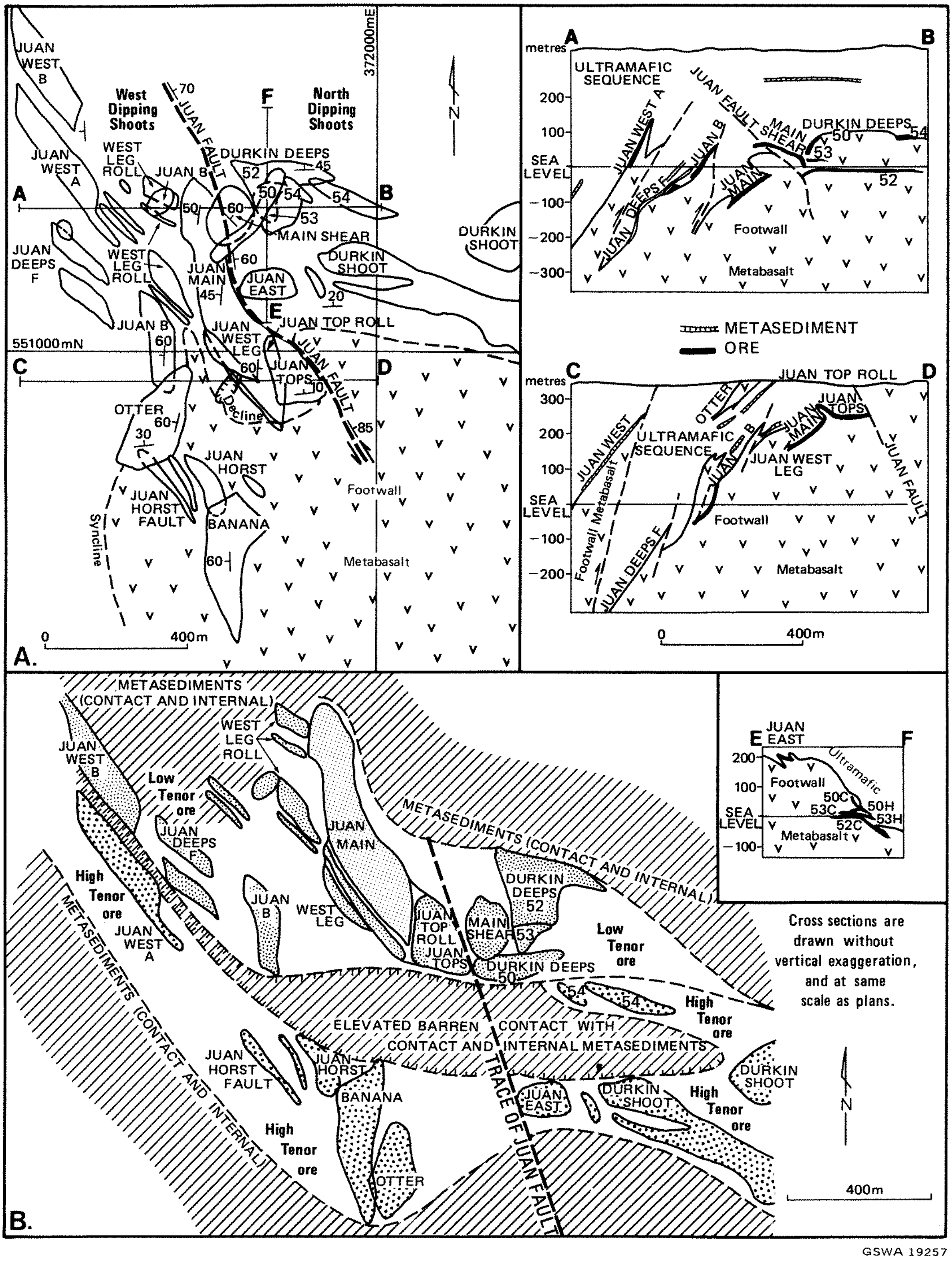

Figure 31. Ore subshoots of Juan complex, Juan West and Durkin Deeps.
A. Present positions of the subshoots (in plan projection) and Juan Fault, with two east-west cross sections.
B. Interpreted reconstruction of original positions of the subshoots before deformaton. The ore shoots are grouped into high- and low-nickel tenor belts with flanking contact and internal (within ultramafic) metasediments.

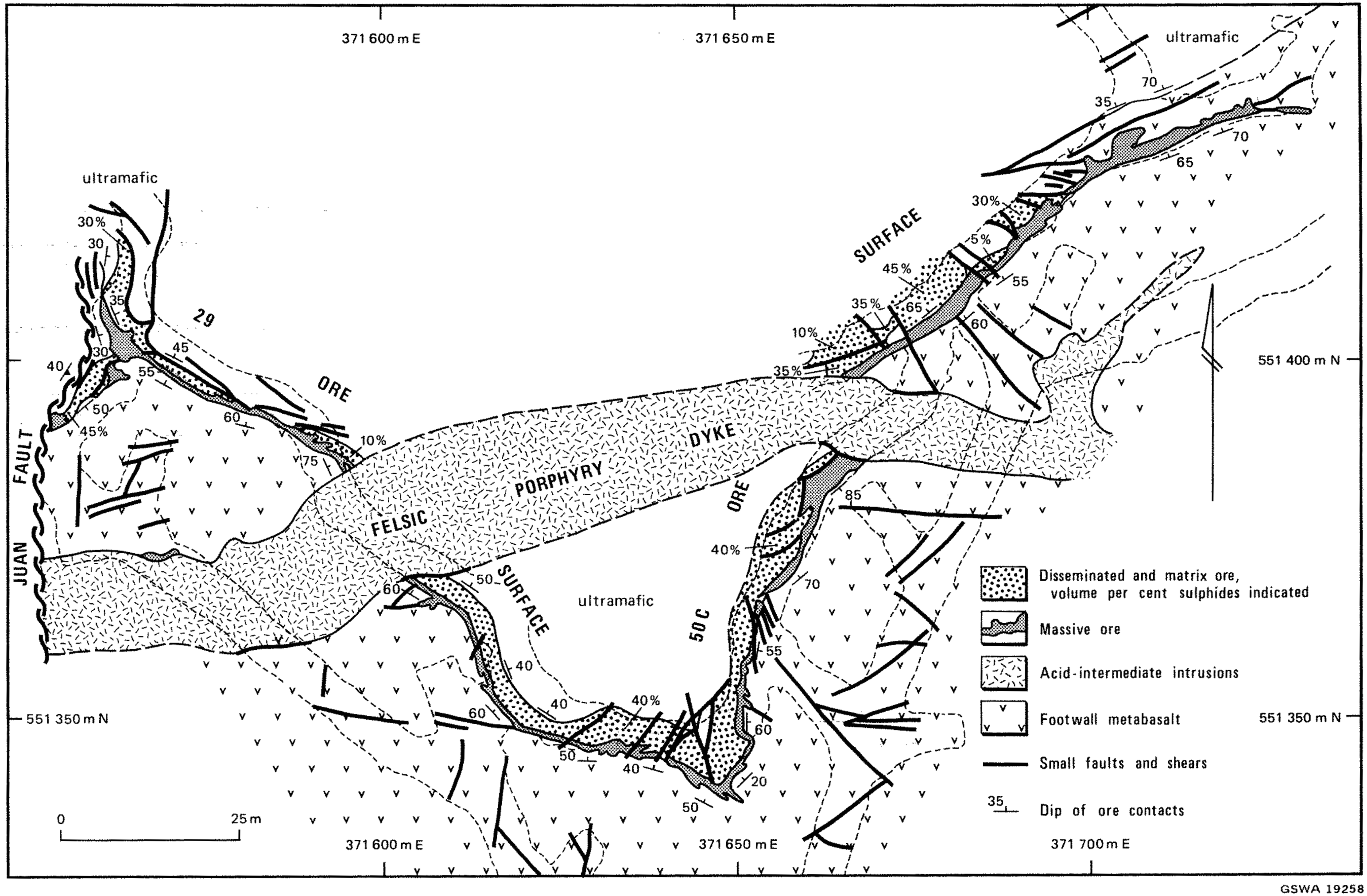

Figure 32. Geological plan of Juan Main Shear (29) subshoot and Durkin Deeps (50C) subshoot as exposed in mine workings on the 10 level (44 m above sea level).

Metasomatic reaction zones containing abundant chlorite, biotite-phlogopite, or tremolite are present between the chemically contrasting metabasalt and ultramafic rocks, or felsic porphyry intrustions and ultramafic rocks. Where contact ore is developed, such reaction zones are only present where massive ore is very thin or locally missing, or where breccia ore is present (e.g. Juan Main 1004 cut and fill stope; Juan Main Shear 829/3 intermediate stope; Juan Banana 234/10 stope).

General structure

The shoots form part of a northeastern belt of ore, with the Durkin, Gibb, Long and Victor shoots, and they straddle the north-northwest plunging anticlinal axis of the Kambalda dome. The Juan Fault occurs in this axial zone and thereby separates the mineralization into north-dipping ore surfaces to the east and generally west-dipping ore surfaces to the west (Fig. 31A). A structural analysis by Kay (1977), published by Marston and Kay (1980), showed that formerly more continuous subshoots have been broken up by large-scale folding (Otter syncline, Kambalda dome) followed by high-angle reverse faulting and finally strike- to oblique-slip movement along the Juan Fault with associated smaller scale folding and low-angle reverse faulting. The footwall metabasalt at Otter shoot appears to be underlain by a low-angle reverse fault whose site was partly controlled by a metasedimentary unit in the ultramafic formation. Further south this overthrust tongue of footwall metabasalt thickens and conceals the underlying Juan Banana and Horst ore surfaces.

West of the Juan Fault the subshoots are bounded by north-trending reverse faults and northwest-trending flexural folds (Kay, 1977). East of Juan Fault most ore is related to a complex north-northwest plunging synclinal structure developed immediately east of the main anticlinal axis of the dome. This structure links the Juan Main Shear (29 surface) subshoot with the Durkin Deeps 50C subshoot (Fig. 31 cross section A-B, and Fig. 32). Anderson (1978) interpreted the development of this fold as being related to rotation caused by sinistral movement along Juan Fault. Another consequence of this rotation may have been the development of low-angle thrusting to the north, in the core and eastern limb of the fold, with lateral displacement decreasing eastwards towards the presumed axis of rotation. These low-angle thrusts carry nickel ore on the subshoots of Durkin Deeps 50H, 52 and 53 (Fig. 31, cross sections A-B and E-F).

A reconstruction of the original configuration of subshoots is given in Figure 31B. This reconstruction shows two arcuate belts of ore with contrasting nickel tenors separated by a horst-like structure, which is interpreted as representing an original topographic high. This horst narrows westwards to Juan West where low- and high-tenor ores are only 40 m apart. In this reconstruction the largest continuous subshoot consists of Durkin Deeps 50, 52 and 53, Main Shear, Juan Tops and Top Roll, Juan Main, West Leg and West Leg Roll with plan dimensions of about 1 000 m by 300 m. Rod-shaped bodies of breccia ore present within the Juan Fault plunge at 25 to 30 degrees to the north-northwest; they are regarded as portions of Juan contact ore which have been involved in the oblique slip-fault movements.

Dyke-like and sill-like felsic intrusives mainly strike west to west-northwest and dip steeply south, except for some in the Durkin Deeps area which dip gently, sub-parallel to the 52 and 53 subshoots. Minor movements post-dating the felsic intrusives are evident on the Juan Fault and parallel to some subshoots (e.g. Juan Main).

Ore distribution and structure

Only one percent of the ore is hangingwall ore and this is largely found as blebby ore in Otter shoot.

In detail any subshoot shows irregular ore distribution and structure. Massive and disseminated-matrix ore are very variable in thickness and commonly have irregular contacts with the footwall metabasalt of the ultramafic formation (Figs 32 and 33). In some subshoots, such as Juan Main (Marston and Kay, 1980) disseminated ore is areally more extensive (by about 15 per cent) than massive ore. In other places, particularly where deformation on the footwall metabasalt-ultramafic contact is more intense (e.g. Juan Banana and Horst, Durkin Deeps 29 — see Fig. 32), the opposite applies, and, typically, conspicuous fragments of wall rocks occur in massive ore (i.e. breccia ore).

Veins of massive ore inclined at various angles to the contact penetrate up to a few metres into the footwall metabasalt , disseminated-matrix ore, or barren ultramafic rock. Rarely such veins intrude felsic intrusives. The typical range of thickness for massive ore is 0.2 to 4.0 m, with the thicker sections (exceptionally up to 10 m in Juan Main) being commonest in (i) the axial zones of folds; (ii) on the margins of subshoots where the ultramafic unit is pinched out by a reverse fault and the ore has a metabasalt footwall and hangingwall; and (ii) marginal to felsic intrusives.

Disseminated to matrix ore is commonly two to seven times thicker than the massive ore which it overlies. Matrix ore is rare as the disseminated mineralization is largely restricted to a sulphide content of 5 to 40 per cent. The top contact of disseminated ore is normally sharp. The low-grade disseminated zone (3 to 4 per cent sulphides) described by Ross and Hopkins (1975) from Lunnon shoot is not generally present except in parts of Otter Shoot.

Most disseminated-matrix ore lacks any penetrative fabric, although its basal contact and more rarely the top contact with the ultramafic rock may be foliated. In contrast the bulk of massive ore has a distinct mineralogical layering (Fig. 33) and contains a fine scale foliation defined by the physical elongation of sulphide grains, trains of spinel grains, and oriented plates of phyllosilicate minerals.

The mineralogical layering in massive ore is mainly defined by alterations of 2 to 10 mm thick pyrrhotite- and pentlandite-rich 'layers', which in detail are lensoid pentlandite aggregates set in a foliated matrix of polycrystalline pyrrhotite (Fig. 88A). This pyrrhotite-pentlandite-rich sulphide commonly makes up at least 90 per cent of massive ore by volume (Fig. 33). Fine-grained pyrite accompanied by minor pentlandite is a subordinate component of massive ore, which occurs as discontinuous layers and scattered lenses both normally confortable with the pyrrhotite-pentlandite layering (Fig. 33). In structurally complicated areas fine pyrite lenses are more abundant, and fine pyrite layers may form discordant veins in massive ore. Here the mineralogical layering as a whole may abut sharply against embayments in the footwall or hangingwall, or contain small-scale flexural to near-isoclinal folds entirely contained within massive ore (Fig. 33).

Single crystal, open-packed aggregates or discontinuous layers of idioblastic pyrite 2 to 15 mm in diameter occur sporadically in massive ore, most commonly near the hangingwall contact with disseminated ore or barren ultramafic rock, immediately adjacent to layers of fine-grained pyrite (Figs 33 and 88A). Most of the chalcopyrite in massive ore accompanies this coarse pyrite. Some coarse pyrite amd most fine pyrite appears to be superimposed texturally on the fine-scale foliation, which passes without deflection through the pyrite. Coarse pyrite is a feature of the extremities of the Durkin Deeps 50H and 53H subshoots, which constitute offset ore in the ultramafic unit (Fig. 31, cross section EF).

Massive ore rarely contains more than 93 weight per cent sulphides. The balance is made up of talc, chlorite, carbonate, amphibole, quartz and spinels. These minerals are dispersed throughout massive ore, but magnetite and lesser amounts of chrome spinels are concentrated at the top and bottom contacts of massive ore as discontinuous layers or lenses. Spinels also occur throughout disseminated-matrix ore but are commonly concentrated at the basal contact with massive ore or footwall metabasalt.

Breccia ore, consisting of silicate rock fragments in a sulphide matrix, does not normally exhibit mineralogical layering, but it is foliated and in places intensely so. The commonest type of breccia ore occurs at the footwall metabasalt-ultramafic formation contact and contains many

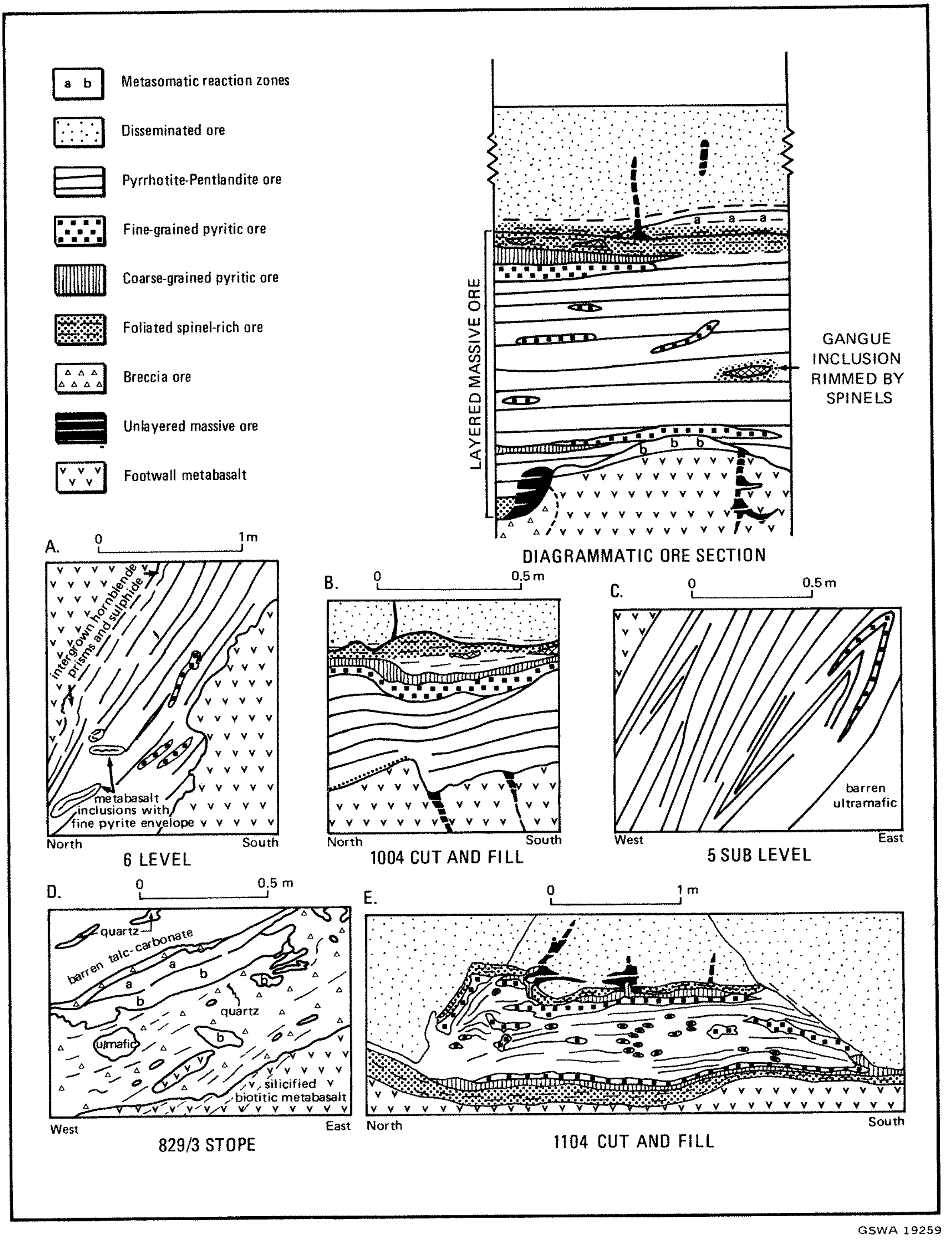

Figure 33. Diagrammatic section through massive ore, showing typical distribution of mineralogical-textural components. Thick lines denote pyrrhotite-pentlandite mineralogical layering, thin lines denote metamorphic foliation. Sketches A to E are of vertical underground faces of ore. A — Durkin Deeps 50; B, C, and E — Juan Main; D — Juan Main Shear (29) subshoots.

deformed fragments of rock from the metasomatic reaction zone, normal wallrocks, disseminated ore, and vein quartz (Fig. 33D). This type is termed *reaction-zone-breccia ore.* In rare cases such breccia ore has intruded through felsic porphyry dykes and contains many angular fragments of porphyry and of deformed reaction-zone rocks developed marginally to such dykes. A less common type of breccia ore, termed *footwall-breccia ore,* occurs in irregular patches in the footwall and consists of angular metabasalt fragments in sulphides. Footwall-breccia ore contains less sulphide (10 to 30 per cent) compared with reaction-zone-breccia ore (30 to 70 per cent sulphides).

Reaction-zone-breccia ore is characteristically developed where the footwall metabasalt-ultramafic contact is more deformed and metasomatically altered, and where *disseminated-matrix ore is thin, sporadically developed or* absent. This applies to much of Juan Fault, Juan West Leg Roll, Juan Deeps F, Juan Banana, Horst and Horst Fault subshoots, and parts of Juan Main, Juan Main Shear (29), Durkin Deeps 52 and 53 subshoots and Otter shoot.

Ore petrology

The opaque mineralogy of all nickel ore types, excepting Otter shoot ores which are discussed separately, is as follows. Monoclinic pyrrhotite and pentlandite are the major phases constituting 90 per cent of the total, with pyrrhotite:pentlandite ratios ranging from about 0.7 in high-tenor ores to 2.5 in low-tenor ores. Pyrite, chalcopyrite and magnetite are minor phases, chrome spinels are important accessories, and arsenopyrite and hematite are rare accessories.

Pyrrhotite occurs in aggregates of grains which are up to 3 mm in diameter but are commonly in the range 0.1 to 1.0 mm in diameter. The grains are generally elongated parallel to the mineralogical layering and fine-scale foliation in massive ore, and exsolved pentlandite flames are common. The orientation of these flames and contrasts in anisotropism indicate that the basal plane is normally subparallel to the foliation. Kink bands oriented normal to the foliation are weakly to moderately developed; spindle-shaped deformation twins are rare (e.g. Juan West). All pyrrhotite is affected by varying amounts of annealing and subgrain development resulting in grains with triple-point contacts, gently curving boundaries and reduced internal strain. The annealing rarely destroys the lensoid pyrrhotite fabric in massive ore. Aggregates in disseminated ore may have no foliation and no strain textures.

Pentlandite is typified by octahedral cleavage and many irregular cracks which are filled by pyrrhotite, chalcopyrite, pyrite or gangue minerals. In pyrite-rich layers and lenses, pentlandite occurs along pyrite grain boundaries along with minor chalcopyrite.

Pyrite present in close-packed aggregates is subidioblastic to ovoid and has a similar size range to pyrrhotite. Idioblastic pyrite develops on the edges of some aggregates, especially in contact with gangue, and as single crystals in sulphide or gangue. Many of the larger pyrites are chemically zoned with nickel being depleted in the cores compared with the rims. Pyrite may also fill grain boundaries and cracks in pyrrhotite and pentlandite. In massive and disseminated matrix ore some pyrite is intergrown with chalcopyrite in a fine-grained, delicate, symplectic-like texture. Chalcopyrite also occurs as separate grains and aggregates, especially in disseminated matrix ore where it is generally more abundant.

Xenoblastic to idioblastic magnetite forms the bulk of the oxide phase, and occurs as small grains dispersed throughout the sulphides and gangue of all ore types. Some grains and aggregates are cracked and veined by sulphides.

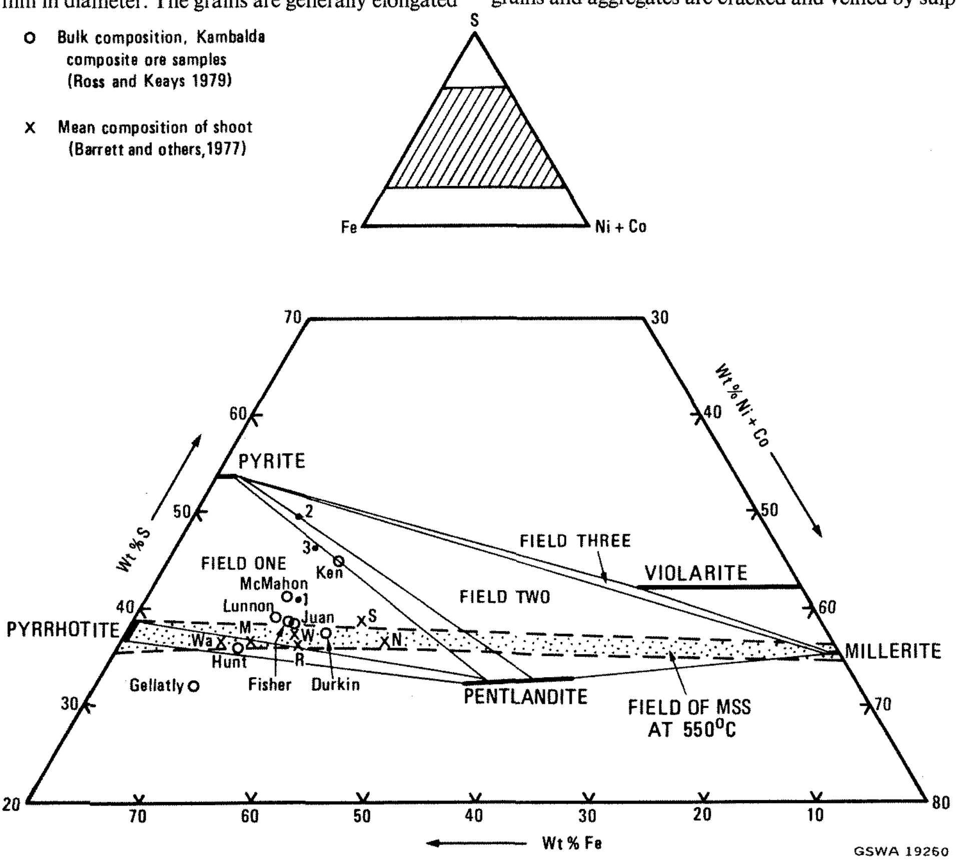

Figure 34. Plot of analyses of sulphide fraction of ores in terms of Fe-Ni + Co-S (wt%) for Juan complex, other Kambalda shoots and other volcanic peridotite-associated deposits. Numbered dots 1, 2 and 3 refer to Juan Main massive ore analyses in Table 33. M = Mount Edwards, N = Nepean, R = Redross, S = Scotia, W = Windarra, Wa = Wannaway.

Composite chrome spinels are eratically distributed, being an abundant accessory or even a minor phase in some ores, but being sparse in others except at the top and bottom of massive ore. These spinels consist of fragmented cores of ferrochromite surrounded by chrome magnetite rims of very variable thickness, and they are comparable with ones described by Groves and others (1977) from Lunnon shoot ore.

Otter shoot ore consists of (i) massive, matrix and disseminated contact ore; and (ii) blebby hangingwall ore in two zones 2 to 10 m thick located 6 to 25 m above the contact ore (Keele and Nickel, 1974). The contact ore occurs as two assemblages:

(a) millerite-pyrite-supergene violarite + chalcopyrite, with rare pentlandite and gersdorffite; and
(b) pyrrhotite-pentlandite entirely pseudomorphed by supergene violarite-pyrite.

The millerite in assemblage (a) is primary and up to 5 cm in diameter in massive ore. The accompanying pyrite is nickel-rich and occurs as coarse grains or is symplectically intergrown with chalcopyrite. Massive ore is fractured and veined by siderite. Massive and matrix ore contain inclusions of tremolitic amphibole and minor chlorite (reaction zone material?) which are 5 to 30 cm in diameter and may have thin rims of magnetite. The overlying ultramafic unit is a talc-serpentine-carbonate rock.

The hangingwall ore at Otter shoot is an assemblage of pyrite-millerite-pentlandite-magnetite + chalcopyrite and rare primary violarite and pyrrhotite, occuring as blebs 1 to 10 mm in diameter (Keele and Nickel, 1974). The blebs make up 5 to 20 per cent of the rock volume, and range in composition from being totally sulphide-oxide to totally silicate-carbonate. The commonest host is a serpentine-talc-carbonate rock. Talc-serpentine or large magnesite porphyroblasts occur in the blebs. The mineral proportions in the opaque assemblage are very variable, but magnetite is always a major component and the amount of pentlandite present is generally inversely proportional to the millerite content.

The composition of the sulphide fraction of Juan Main ores and of a composite Juan complex ore are given in Table 33, and these compositions are plotted in the Fe-Ni-S system in Figure 34. The nickel content of some massive ores is given in Table 32. Layered massive ore from Juan Main shoot shows little compositional variation with the exception of copper. Unlayered massive ore and breccia ore are more variable and are richer in sulphur, copper and cobalt compared with layered massive ore. This probably reflects a greater pyrite and chalcopyrite content. Marston and Kay (1980) found that pyrite in breccia ore was cobalt-rich. Limited data indicate that disseminated ore is similar in composition to layered massive ore, with the exception that copper is higher in disseminated ore. Chalcopyrite is conspicuous in some stringers and veins cutting footwall metabasalt, disseminated ore or the ultramafic unit.

The bulk composition of Juan complex ore is very similar to that of Fisher and Lunnon ore (Table 31, Fig. 34). Ore from these an most other Kambalda shoots plots on the sulphur-rich side of the monosulphide solid solution field in the ternary diagam Fe-Ni-S (Fig. 34) Juan Main massive ores show a trend towards greater sulphur enrichment particularly in the unlayered and breccia ores. The ores at Otter shoot would be expected to plot in fields one (pyrite-pentlandite-pyrrhotite), two (pyrite-millerite-pentlandite) and three (pyrite-violarite-millerite) in Figure 34.

Supergene violarite-pyrite ore and transitional ore is restricted to the upper levels of the mine in Juan East, Otter and Juan Roll subshoots particularly. Violarite may occur at deeper levels where the ore is affected by pervious shear or fault zones (e.g. Juan B subshoot).

DURKIN SHOOT (31°09′50″S, 121°39′20″E)

Introduction

Durkin shoot occurs to the east of the Juan complex and the Durkin Deeps shoot and is spartially related to them by the adjacent Juan East and Durkin Deeps 54 subshoots which carry high-tenor nickel ore, as does Durkin shoot itself (Fig. 35). A small, fault-bounded tongue of mineralized ultramafic rock gives a soil geochemical anomaly and a few small gossanous outcrops are present, samples of which assay 0.14 to 1.5 per cent nickel and 0.13 to 1.3 per cent copper (Mazzucchelli, 1972). A gossan sample analyzed by Travis and others (1976) contained 1.78 per cent nickel, 4.48 per cent copper, 147 ppb palladium and 1 940 ppb iridium.

Durkin mine began production in early 1969. The mine originally employed two vertical shafts for ore haulage (309 m deep) and servicing but only one is now used. Rail-mounted mining equipment is used on the eight underground levels developed. Mining is done by slot stoping with pillars being recovered with the aid of hydraulically placed sand fill. Pre-mining reserves place the

TABLE 33. GEOCHEMISTRY OF THE SULPHIDE FRACTION OF SOME JUAN ORES

A. Compositions in weight per cent of large hand specimens, Juan Main (Marston and Kay, 1980)

Mean compositions (standard deviation shown in brackets)	Fe	Co	Ni	Cu	Zn	S	Total Sulphide	Ni/Co	Ni/Cu	Fe/Ni
1. Layered massive po-pn ore (10 samples)	40.3 (4.1)	0.157 (0.07)	12.2 (2.06)	0.58 (0.84)	0.011 (0.012)	36.4 (0.7)	89.9 (5.2)	77	21	3.3
Elements in 100% sulphides	44.9	0.17	13.6	0.65	0.012	40.5				
2. Unlayered massive ore (4 samples)	33.2 (5.7)	0.424 (0.209)	7.8 (3.7)	1.60 (1.87)	0.028 (0.022)	40.1 (4.5)	83.2 (8.4)	18	5	4.2
Elements in 100% sulphides	39.9	0.51	9.4	1.92	0.034	48.2				
3. Breccia ore (4 samples)	27.9 (11.5)	0.331 (0.288)	8.2 (5.4)	0.85 (0.88)	0.026 (0.028)	30.6 (12.6)	67.2 (26.6)	25	10	3.4
Elements in 100% sulphides	41.5	0.49	12.2	1.26	0.039	45.5				

B. Mean *bulk* compositions in weight per cent of complete drillcore intersections of massive ore and disseminated ore from Juan Main obtained by L.A.G. *Hissink (unpublished data).*

Massive ore (26 samples)	Mean	Standard deviation	Range	Disseminated ore (33 samples)	Mean	Standard deviation	Range
Ni	12.16	1.84	5.90-13.90	Ni	4.20	0.83	2.54- 5.52
Cu	0.81	0.70	0.14- 3.20	Cu	0.33	0.14	0.15- 0.80
Co	0.27	0.27	0.16- 0.42	Co	0.08	0.01	0.03- 0.10
Ni/Cu	26.31	24.49	2.59-77.73	Ni/Cu	14.14	3.97	4.66-23.02
Ni/Co	47.17	13.33	14.75-81.88	Ni/Co	52.05	10.68	36.07-89.25
Specific gravity	4.66	0.12	4.43- 5.06	specific gravity	3.36	0.08	3.16- 3.51

C. Elements in 100 per cent sulphides in composite sample of mined Juan complex ore (Ross and Keays, 1979).
Fe:46.7 Co:0.29 Ni:14.1 Cu:0.95 S:38.0

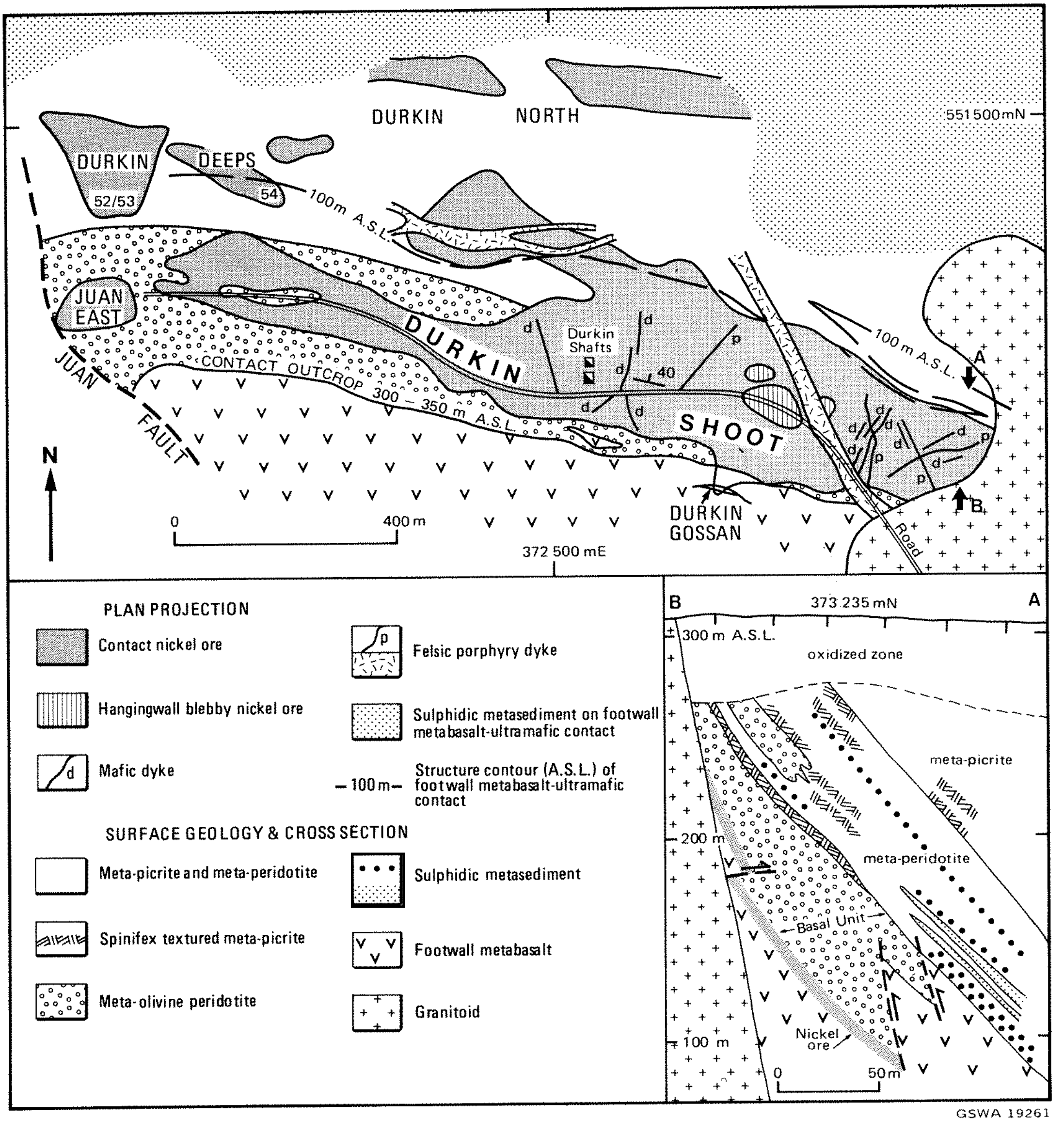

Figure 35. Geological plan and cross section of Durkin shoot (from Hayden, 1976).

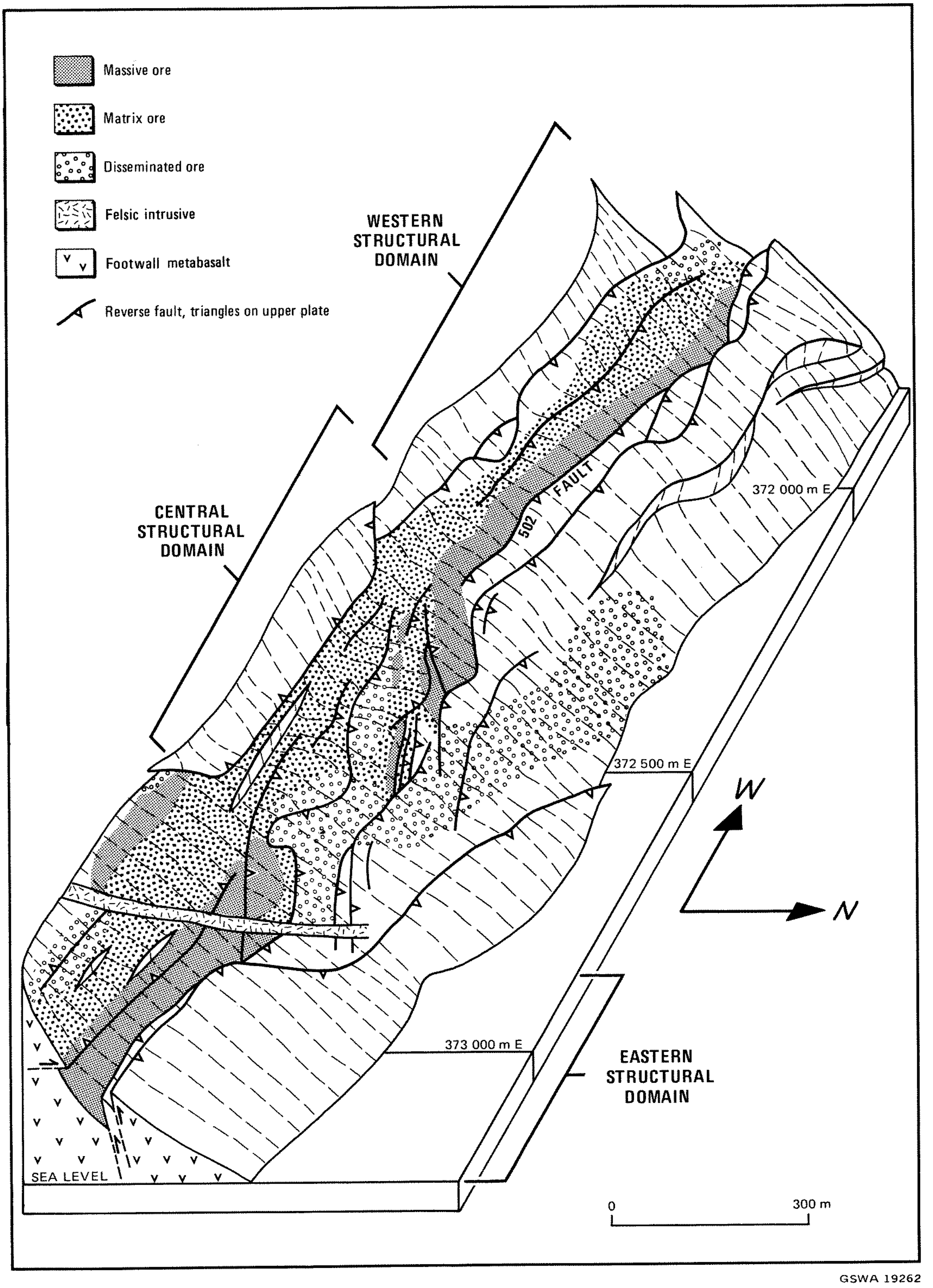

Figure 36. Isometric projection (looking west) of Durkin shoot showing the footwall metabasalt-ultramafic contact, major reverse faults and the distribution of ore types on the contact (from Hayden, 1976).

shoot in category 2 (Fig. 26). Ore reserves are now very limited and in 1980 the mine completed its last year on full production with an expected 'winding down' period of a further four years. Mining of the Durkin North mineralization, which is down dip from Durkin shoot, would require access from the Durkin Deeps workings to the west.

Stratigraphy

The basal member exposed in the mine generally correlates with the basal unit of the Kambalda ultramafic formation, and is 25 to 55 m thick. The upper member exhibits good flow-unit development where intersected in drillholes in the deeper northeastern part of the shoot. Metasediment is absent from the footwall metabasalt-ultramafic contact for distances of 140 to 300 m from the downdip limit of Durkin shoot, but metasediment occurs immediately adjacent to Durkin North (Fig. 35). Metasediment present within the ultramafic overlaps the northern half of the shoot in plan projection.

The ultramafic host is dominantly a dark-green antigorite serpentinite, which contains relict igneous olivine in the east, but talc-carbonate-bearing rocks are present in the west. Quartz, talc, or carbonate veinlets occur locally. Foliation is absent except for the basal few metres of the ultramafic unit, and, in some places, the contact zone. In both situations the foliation is parallel to the contact. The footwall metabasalt is fine to medium grained and unfoliated except adjacent to some contacts with the ultramafic host. Patchy epidotic or biotitic alteration is present in some of the metabasalt. Faults affecting metabasalt may be marked by a thin zone of foliated amphibolite or a thin margin of metabasalt containing medium- to coarse-grained hornblende prisms forming a static metamorphic texture.

Metasomatic reaction zones occur on the footwall metabasalt-ultramafic contact and marginally to felsic and mafic dykes. Reaction zones on the contact are commonest away from mineralized areas.

General structure

Durkin shoot has a strike length of some 1 500 m in the direction 285 degrees, a width in plan projection of 100 to 300 m, and a dip to the north-northeast of about 40 degrees (Fig. 35). With the exception of a northern lobe of disseminated ore, the shoot is confined downdip by mainly high-angle reverse faults which dip steeply to the north-northeast and foreshorten the contact in plan projection (Fig. 35 cross section, Fig. 36). To the south the shoot is not confined tectonically, except for an area south of the shafts where a reverse fault dipping at low to moderate angles to the north has moved a plate of metabasalt northwards over the shoot (Fig. 36). The plunges of the resulting fault-bounded surfaces are generally at low angles to the east-southeast.

The shoot is truncated to the east by a large mass of intrusive granitoid. A large northwest-trending, felsic porphyry divides the eastern portion of the shoot. East of this dyke numerous small felsic and mafic dykes cut through the ultramafic unit and footwall metabasalt, but are themselves folded, faulted or boundinaged where they pass across contact ore or a barren footwall metabasalt-ultramafic contact (Hayden, 1976, and Fig. 37).

Ore distribution and structure

Hayden (1976) divided the shoot into three structural domains, termed western, central and eastern structural domains (Fig. 36). In the western domain matrix ore 1 to 2 m thick is dominant, and this changes to massive ore within 20 to 40 m of the 502 reverse fault (Figs. 36 and 38). Oblique-slip reverse faults are characteristic of the central domain and massive ore is mainly found near these faults. Matrix ore is still dominant but there are large areas of the contact zone carrying disseminated ore only. This disseminated ore tends to increase in sulphide content near the faults. In the eastern domain, massive ore, averaging 0.5 m in thickness and generally lacking any disseminated ore above, is mainly restricted to a fault-bounded trough. Matrix and disseminated ore occurs at higher mine levels on the contact. Some massive ore is restricted to 1 to 2 m deep, sharply bounded hollows up to 30 m long in the top of the footwall metabasalt.

Hangingwall ore is restricted to three bodies of blebby ore in antigorite serpentinite (Fig. 90A), adjacent to the large porphyry dyke in the eastern structural domain (Fig., 35). The largest of these bodies measures 130 m by 65 m in plan and is up to 20 m thick. None of the bodies appears to be structually controlled in terms of shape or position. Blebby ore occurs up to 40 m above the footwall metabasalt-ultramafic contact, but most is within 10 m of this contact. Most blebby ore consists of 5 to 10 per cent sulphides by volume.

Matrix, disseminated and blebby ore generally lacks any foliation, but massive ore contains mineralogical layering and a fine-scale foliation as described previously for Juan complex ore. Lenses and layers of fine-grained pyrite are present in most primary massive ore. Coarse primary pyrite seems to be rare. Reaction zone breccia ore is common, especially in the eastern structural domain. Some massive and blebby ore contains a mineral lineation or foliation which is oblique to the main layering and foliation (Hayden, 1979).

Ore petrology

Ore above the 2 level consists of supergene violarite and pyrite plus relict chalcopyrite. Transition-zone ore consisting of pyrrhotite-pentlandite-violarite-primary pyrite plus chalcopyrite is volumetrically the most important type, being present from the 3 to the 8 levels. Cubanite was noted from one sample of breccia ore. Primary ore is generally similar in mineralogy to Juan complex ore, and the pyrrhotite:pentlandite ratio is about one, resulting in a nickel tenor for massive ore of some 16 per cent. Some blebby ore consists of pentlandite-millerite-pyrite with minor chalcopyrite and magnetite, and accessory pyrrhotite. Sulphide mineral proportions vary from bleb to bleb. The blebs are up to 10 mm in diameter and form 5 to 10 per cent of the rock. Nickel tenor of most blebby ore is 0.5 to 3.0 per cent.

The textures and distribution of pyrrhotite, pentlandite, pyrite, chalcopyrite, magntite and chromite are similar to those described for Juan complex ores. Both sulphide and oxide phases in matrix, blebby or disseminated ore show a static metamorphic textural intergrowth with silicate minerals. Hayden (1976) has described textural and grain-size changes in massive ore developed in matrix ore marginal to reverse faults. This is illustrated in Figure 38. As the massive ore is traced towards the fault the grain size of sulphides and oxides increases, lenses of fine-grained pyrite become abundant, and pyrrhotite shows the effects of increased internal strain (i.e. kink bands are more marked; deformation twins appear).

A bulk composition for Durkin shoot ore is given in Table 31, and this composition is plotted in terms of Fe-Ni-S on Figure 34. The bulk of the individual ore types would plot in field one (Fig. 34), and some blebby ore would plot in field two, being similar in composition to blebby ore at Otter shoot.

Durkin North mineralization

This contact mineralization occurs 500 m north of the Durkin shafts (Fig. 35). It is confined by a horst structure to the south, and appears to be replaced by sulphidic metasediment northwards and westwards, thus outlining a mineralized contact area about 500 m long and 70 m wide in plan projection (Randell, 1975). The contact is intruded by felsic porphyry. Massive ore up to 15 cm thick, assaying between 8 and 14 per cent nickel, is overlain by disseminated ore up to 2.5 m thick, assaying up to 5 per cent nickel. Demonstrated geological reserves make it a category 6 deposit.

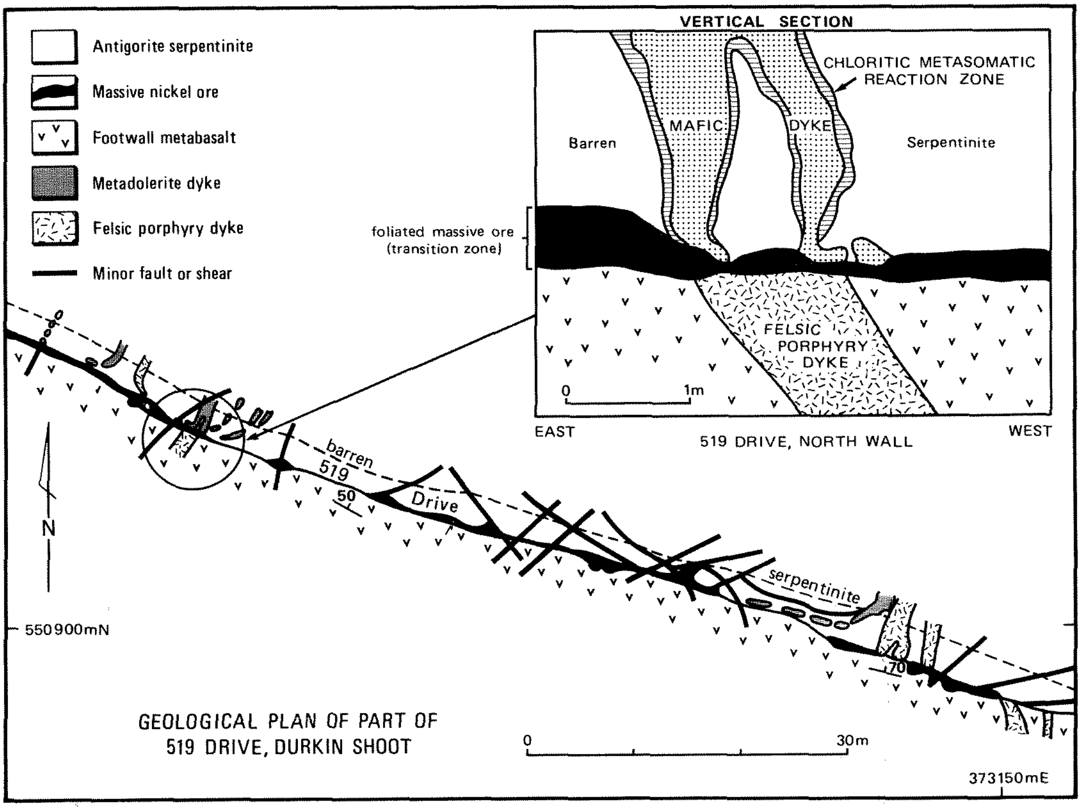

Figure 37. Geologicl plan of part of 519 drive, Durkin shoot, and a sketch of a vertical underground face in the drive.

GIBB AND LONG SHOOTS 31°10′25″S, 121°40′20″E)

Introduction

These shoots occur to the southeast of Durkin shoot, being separated from it by a large mass of acid intrusive rock. Both shoots lack any surface expression. They were outlined by systematic drilling in 1973.

Development ore was first produced from Gibb shoot in late 1977. Development is currently proceeding from five levels (Fig. 39), with broken rock being extracted from the 4 level which is connected by a drive to the 7 level at Durkin mine. The Gibb workings are also serviced by a 3 m-diameter raise bore hole equipped with a hoist and gig for man riding. Sinking of Long shaft began in July 1975 and was completed to a depth of 936 m below the collar in May 1979. Development at Long mine is proceeding, with early work being concentrated on the ore and mullock pass system and loading stations below the 11 and 17 levels. The pre-mining reserves at Gibb shoot place it in category 4 (Fig. 26), whereas Long shoot is a category 2 deposit.

Stratigraphy

The basal unit of the Kambalda ultramafic formation is up to 100 m thick and the basal member may be up to 150 m thick. Metasediment is generally absent from the footwall metabasalt-ultramafic contact, and metasediment within the ultramafic unit is rare except at the north end of the Long shoot.

The ultramafic host at Gibb shoot is mainly undeformed talc-magnesite-chlorite rock with antigorite-bearing rocks predominating at Long shoot. In Gibb shoot the basal few metres of the ultramafic unit is commonly of peridotitic composition, consisting mainly of fine-grained talc and chlorite. This rock is foliated subparallel to or at an angle to the contact. The footwall metabasalt in Gibb shoot is commonly intensely fractured and partly altered to biotite- and epidote-bearing varieties; it is less altered further south. Quartz veins may be common in the footwall metabasalt-ultramafic contact zone. Cross cutting intrusions of pink to grey quartz-feldspar porphyry are abundant in both shoots and occupy much of the footwall metabasalt-ultramafic contact. A few intrusions are sub-parallel to the contact. Mafic intrusions are rare. Many intrusions are themselves strongly fractured and veined by quartz, and affected by hematitic alteration. Some dykes are boudinaged and have deformed envelopes of metasomatic reaction zone material.

General structure.

In plan projection both shoots have a long dimension oriented north-northwest, which measures about 1 800 m for Long shoot and 1 300 m for Gibb shoot, and a width of up to 100 m. Dips are commonly in the range 40 to 60 degrees eastwards for Gibb shoot, and 65 to 80 degrees eastwards for Long shoot, which is situated down dip from Gibb shoot and is separated from it by a horst-like structure defined by a footwall metabasalt-ultramafic contact devoid of ore (Reeve, 1977). Gibb shoot has a dip extent from near surface to just above sea level, whereas Long shoot extends from 40 to at least 540 m below sea level.

Gibb shoot is divided into northern and southern parts by a large mass of intrusive porphyry. The northern part of the shoot is in turn subdivided into two sections (Fig. 39) by a west-dipping high-angle reverse fault, known as

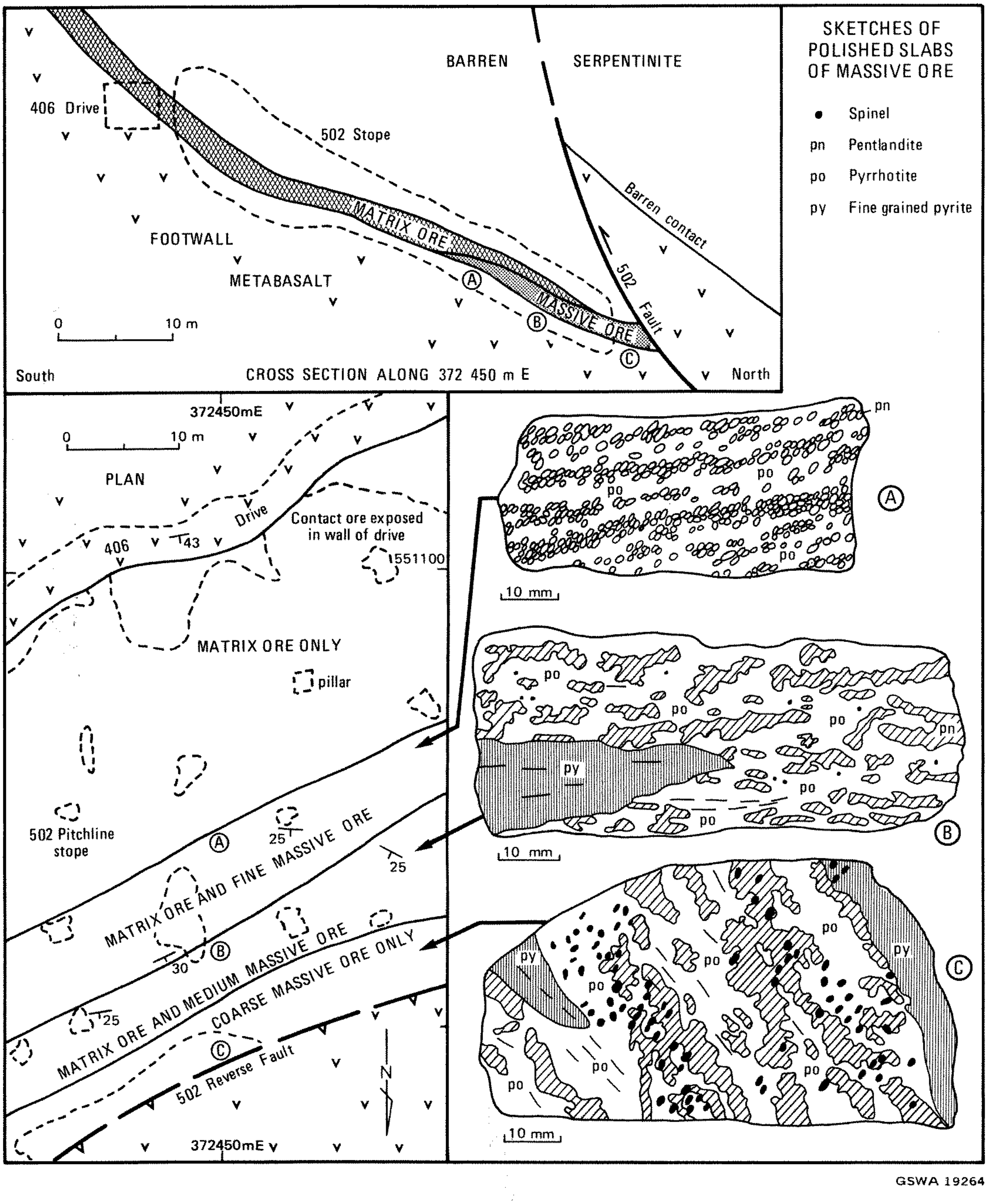

Figure 38. Geological plan and cross section of part of 502 pitchline stope, Durkin shoot, and sketches of textures in massive ore adjacent to 502 reverse fault.

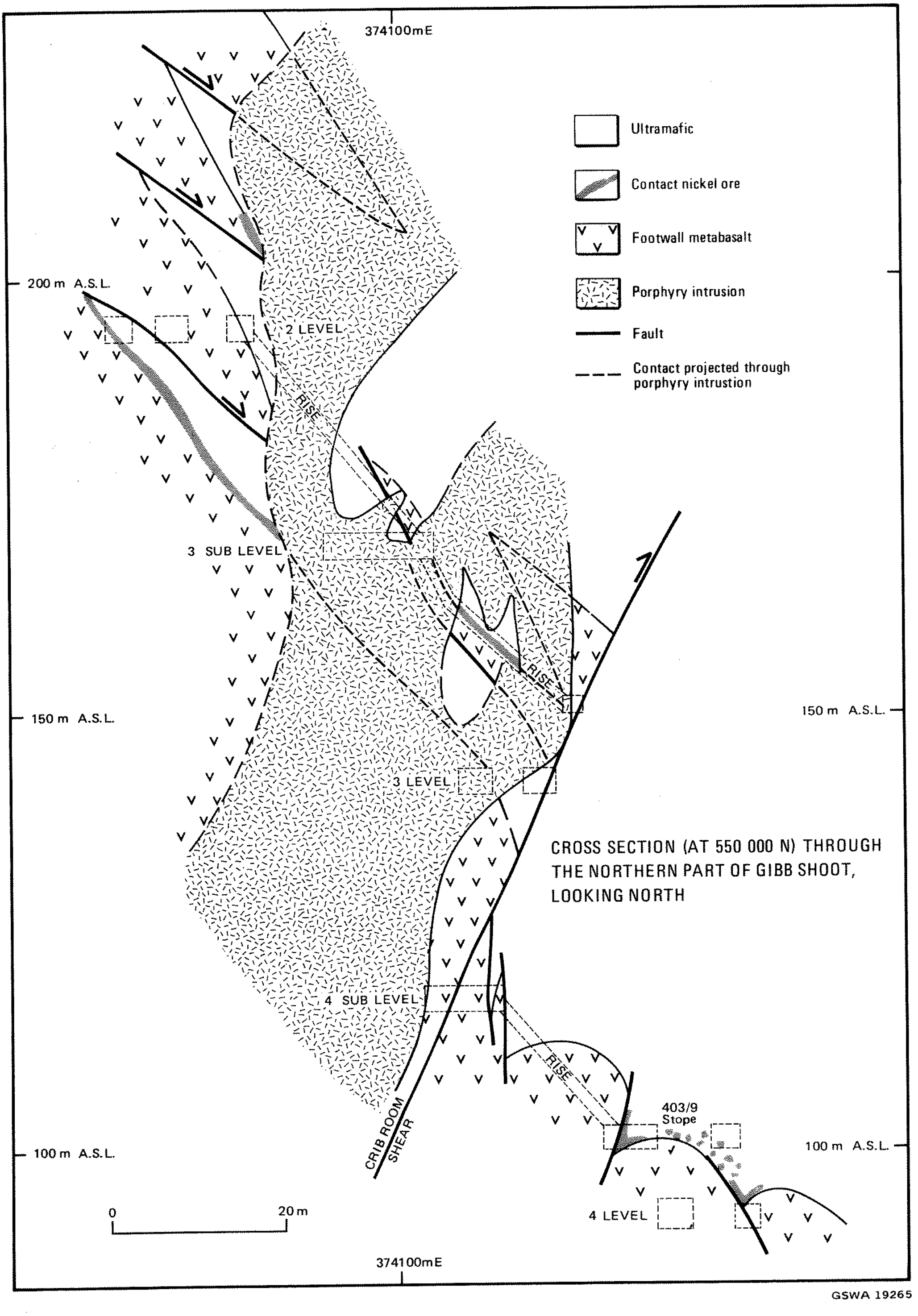

Figure 39. Cross section (at 550 000 N) through the northern part of Gibb shoot, looking north (from Quick, 1978).

the 'Crib Room Shear', which corresponds with a 2 m-wide zone of sheared rock with quartz veins. Some of these veins contain iron sulphides and gold. This fault post-dates the folding and the generally east-dipping reverse faulting affecting the shoot, and it appears to deform some porphyry intrusions. The overall plunge of the northern part of the shoot appears to be gently to the north-northwest. The southern part of the shoot consists of a narrow trough and a poorly mineralized flanking footwall metabasalt-ultramafic surface disrupted by more steeply dipping reverse faults, with nickel sulphides restricted to fractures in the footwall metabasalt beneath a chloritic contact zone.

Long shoot is also divisible into northern and southern parts, according to Reeve (1977). The northern part, which is also referred to as Long West and Long Central, consists of a simple east-dipping surface which is bifurcated southwards by a strike fault. This fault has an increasing throw as it is traced south. The southern part, also known as Long East, is down dip of the projected northern part and occurs within a trough-like structure which has a dip extent of more than 250 m and a plunge extent of more that 1 800 m. The shoot appears to plunge gently northwards in the north and gently southwards in the south.

Ore distribution and structure

Both shoots contain only contact nickel ore, some of which is offset.

In the northern part of Gibb shoot, Quick (1978) reported that massive ore is commonest in or adjacent to areas where the ultramafic host is faulted out by metabasalt wedges, or in small pods in smaller tectonic irregularites in the footwall (Fig. 40). Massive ore is rarely more than 1 m thick (average 10 cm) and some of it is breccia ore. Matrix ore is rare, and disseminated ore contains mainly less than 10 per cent sulphides occurring as blebs and stringers following fractures and small faults. In general, ore distribution and grade are very irregular and contact ore sections are less than 1 m thick. This appears to be partly the result of abnormally intense deformation in the ore zone, although the ores themselves are not distinctly layered or foliated. This strong deformation also appears to characterize the southern part of the shoot where massive ore is rare and much nickeiferous sulphide occurs as veinlets in the footwall metabasalt.

Long shoot contains massive and breccia ore (present in half the diamond drillhole intersections available in 1977) and matrix to disseminated ore. Matrix ore may occur within or at the base of disseminated ore. Massive ore examined in three drillhole intersections is not distinctly layered or foliated though the thick intersection in KD 5084 (703.65 to 714.15m) contains abundant layers and lenses of fine-grained pyrite, oriented at various angles to the axis of the drillcore. Sections of contact nickel ore may be 10 to 20 m thick in drillcore.

Ore petrology

Gibb shoot is characterized by high-tenor nickel ore which consists of (a) pentlandite-pyrite and chalcopyrite, or (b) millerite-pyrite-magnetite with only rare chalcopyrite.

Assemblage (a) is commonest and is typified by cracked aggregates or single idioblasts of pyrite, up to 15 mm in diameter, distributed evenly throughout a matrix of cracked pentlandite. Most of the chalcopyrite occurs as inclusions in the pyrite along with small grains of magnetite, zoned chromite and gangue. Large, zoned chrome spinels 1 to 2 mm in diameter are dispersed sparsely throughout the ore. A few pyrite idioblasts less than 1 mm in diameter are scattered through the pentlandite matrix. Fine-grained magnetite, occurring in aggregates that may be several tens of centimetres long, is present within, and marginal to, massive ore, and inclusions of porphyry are rimmed by magnetite (Fig. 40B). Massive ore assays in the range 12 to 25 per cent nickel, and appears to lack distinct mineralogical layering and any fine-scale foliation. Pentlandite is partly converted to violarite in the topmost levels of the mine.

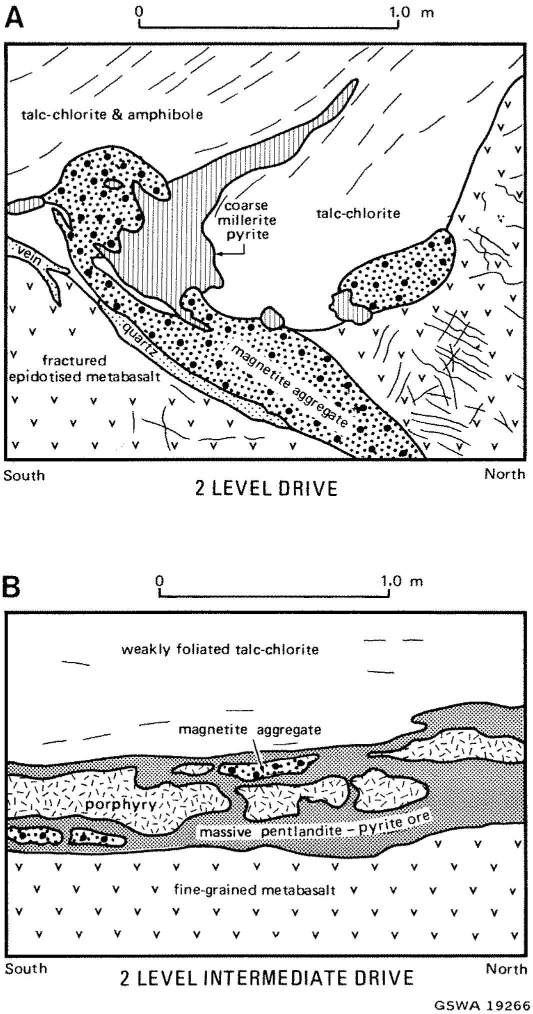

Figure 40. Sketches of vertical underground faces of contact ore in northern Gibb shoot. A — pods of massive, coarse-grained millerite-pyrite ore and associated magnetite aggregates in a footwall depression. B — massive pentlandite-pyrite breccia ore from the same contact as A.

The milleritic assemblage (b) as exposed in current workings, is largely restricted to the 403/1 and 403/9 stopes (Fig. 39) and isolated areas on the 2 level drive (Fig. 40A), according to Quick (1978). Distribution of the ore type appears to be related to small faults or structural irregularities affecting the footwall metabasalt-ultramafic contact. The massive ore is striking in appearance, consisting of irregular megacrysts of millerite up to 8 cm in diameter, which enclose idioblastic pyrite crystals commonly 0.5 to 5 mm in diameter. The millerite may be partly converted to violarite but the conspicuous cleavage parallel to $(10\bar{1}1)$ is retained. Small inclusions of magnetite and gangue are scattered through the millerite, but a more noticeable feature is the presence of aggregates of fine-grained magnetite as thick pods intimately associated with the ore (Fig. 40A) or as thin envelopes around it. Zoned chromites are rare in these aggregates but some magnetites contain tiny globular inclusions of sulphides. Milleritic massive ore may assay up to 45 per cent nickel. In drillcore from KD 5041 weakly developed blebby and disseminated sulphides occur from 158.53 to 161.20 m, which is some 40 m above the depth at which contact ore was intersected by the drillhole. The blebs and disseminations contain millerite, pentlandite and possibly pyrite.

Long shoot is typified by low-tenor pyrrhotite-pentlandite ore although Reeve (1977) records minor millerite from the upper part of the northern end of the shoot (e.g. drillhole KD 5053). The massive ores examined were either fine-grained pyrrhotite-rich ore or coarser grained, pyritic breccia ore neither of which are well layered. The fine-grained ore is richer in sulphides and assays 10 to 15 per cent nickel, whereas the breccia ore assays 7 to 10 per cent nickel. The fine-grained ore consists of subsequent pyrrhotite grains 0.1 to 1.0 mm in diameter which contain kink bands and a few deformation twins, and are annealed into granular mosaics. Pentlandite grains, of similar size to the pyrrhotite, occur in irregular aggregates. Pyrite, some intergrown with chalcopyrite, is present along the grain boundaries of pyrrhotite. Small rounded magnetites are dispersed throughout the ore. The coarse-grained, pyritic breccia ore contains quartz and wallrock fragments, and inclusions of magnetite-rich aggregates.

The matrix and disseminated ores show good intergrowth and recrystallization between sulphides and silicates. Pyrrhotite and subordinate pentlandite are the main sulphide phases, with minor chalcopyrite and rare pyrite. Magnetite and zoned chromite are dispersed throughout most ores, and in places may make up to 10 per cent of the rock.

VICTOR SHOOT (31°11′30″S; 121°40′55″E)

Victor shoot is along strike to the south-southeast of Gibb shoot, being separated from it by a large mass of acid intrusive rock. The shoot has no surface expression. It was discovered by systematic drilling shortly after Gibb and Long shoots were outlined. Preparations for sinking a shaft were completed in 1977 but further work was suspended because of a decision to reduce mine production. Victor shoot is a category 4 deposit (Fig. 26), but reserves are based on only a small number of diamond drillhole intersections.

The basal unit of the Kambalda ultramafic formation is 50 to 150 m thick and generally makes up the whole of the basal member, with the greater thicknesses occurring towards the south-southeast. Flow units are well developed in the upper member of the formation. Metasediment is present on the footwall metabasalt-ultramafic contact to the west and southeast of the shoot. Felsic porphyries intrude the contact to the west and south of the shoot. Several horizons of metasediment occur within the ultramafic unit and immediately to the south and west of the shoot. The ultramafic host is an undeformed, granular antigorite serpentinite which is weakly affected by talc-carbonate alteration in places.

The shoot in plan projection is 800 m long (north-northwest) and up to 120 m wide in the north, and coincides with a shallow trough-like structure gently south and dipping at about 45 degrees to the east (Plate 2, section EF). At its midpoint the shoot is 250 to 350 m below sea level.

The mineralization of economic interest is restricted to the Victor Main Contact subshoot (Plate 2 section EF), although minor contact nickel sulphides occur at Victor West, and weakly developed blebby hangingwall sulphides have been intersected in the trough-like structure to the west of the Victor West subshoot. Massive, matrix and disseminated ores are present and in general are of high tenor because of an abundance of pentlandite. Massive ore assays 14 to 18 per cent nickel and consists of medium to coarse-grained pentlandite, fine-grained pyrrhotite, plus minor chalcopyrite, and coarse- or fine-grained pyrite crystals and lenses, as in other Kambalda massive ore. A layer of massive magnetite 5 mm thick, underlies 6 cm-thick massive sulphides in drillhole KD 6041, and magnetite or mixed magnetite-sulphide layers up to 20 cm thick occur in the footwall of the ore zone in KD 6037. This association of abnormally thick magnetite segregations with pentlandite-rich ore is comparable with Gibb shoot.

The matrix ore examined is also pentlandite-rich, and typically assays about 10 per cent nickel, equivalent to many low-tenor massive ores elsewhere. Antigorite is intergrown with fine-grained pentlandite, chalcopyrite and magnetite in a static metamorphic texture (Fig. 94D), which is superimposed on a fine foliation in some places.

LUNNON SHOOT (31°12′50″S; 121°40′50′E)

Introduction

Lunnon shoot occurs at the southern end of the Kambalda dome on the eastern side of the anticlinal axis (Fig. 28). The discovery of this, the first exploited nickel mineralization in the State, is described in Chapter 1. Gossans related to mineralization in the northern part of the shoot crop out poorly near Silver Lake shaft. The average assay of five samples of gossan after massive sulphides analyzed by Travis and others (1976) is 0.54 per cent nickel, 0.61 per cent copper, 219 ppb palladium, 296 ppb iridium and 526 ppb gold. The highest individual value is 1.14 per cent nickel, accompanied by 0.74 per cent copper.

The shoot is exploited by means of the vertical Silver Lake shaft (510.5 m deep) and 9 underground levels equipped with rail-mounted haulage and mining machinery. The 11 Level (380 m below the shaft collar) is the deepest currently operating level. Mining is carried out by slot or cut and fill stoping methods using hydraulically placed sand fill. In November 1973 a crosscut from Lunnon 7 level intersected the E Zone hangingwall ore of Hunt shoot, some of which was then mined and extracted via Silver Lake shaft in the period July 1974 to August 1977.

Lunnon shoot is the second largest shoot (a category 2 deposit) in the Kambalda group, and has been one of the major producing mines in the group for over a decade. Consequently, remaining reserves are now depleted. Full production from the present shaft is expected for a further two to three years, with declining output for a further four years thereafter. Many of the currently producing areas are 1 000 to 1 500 m south-southeast of the shaft. Access to the deeper (12 to 15 levels) part of the deposit may be taken from the Hunt decline using rail-haulage equipped crosscuts.

Stratigraphy

In mineralized areas the basal unit of the Kambalda ultramafic formation (Table 28) is the same as the basal member, and is 50 to 100 m thick. South of the southern limit of the Lunnon Trough (about 545 000N, Fig. 41), the basal unit thins to less than 50 m in parts, and beyond the southern limit of the shoot is less than 25 m thick (Gresham, 1978). The basal unit thins markedly when traced east or west out of the Lunnon Trough. Well developed flow units occur in the upper member overlying the central and southern part of the shoot. The position of the shoot corresponds to a corridor free of metasediment on the footwall metabasalt-ultramafic contact (Fig. 41) or within the ultramafic host. Nickel ore and metasediment are locally found together in the Top Surface East subshoot. Two or more metasediments occur in the ultramafic rock adjacent to the shoot. Most metasediments are of the cherty type. Two metasedimentary horizons 5 to 10 m apart, are present in the footwall metabasalt, about 230 m below the contact with the ultramafic unit; they are exposed in the 11 level plat area.

The basal unit probably averages about 40 per cent magnesia as a whole (Ross and Hopkins, 1975). The B zone is uniform in composition along strike, and the A zone is spinifex-textured and up to 15 m thick; the "Lunnon metapicrite" of Ross and Hopkins (1975) probably represents this A zone. Most meta-olivine peridotite of the B zone consists of granular-textured talc-magnesite + chlorite + dolomite, though some antigorite-bearing rocks are present in the northern and southern parts of the shoot.

The footwall metabasalt is a fine-grained dark grey-green massive rock which is locally epidotized or biotitic.

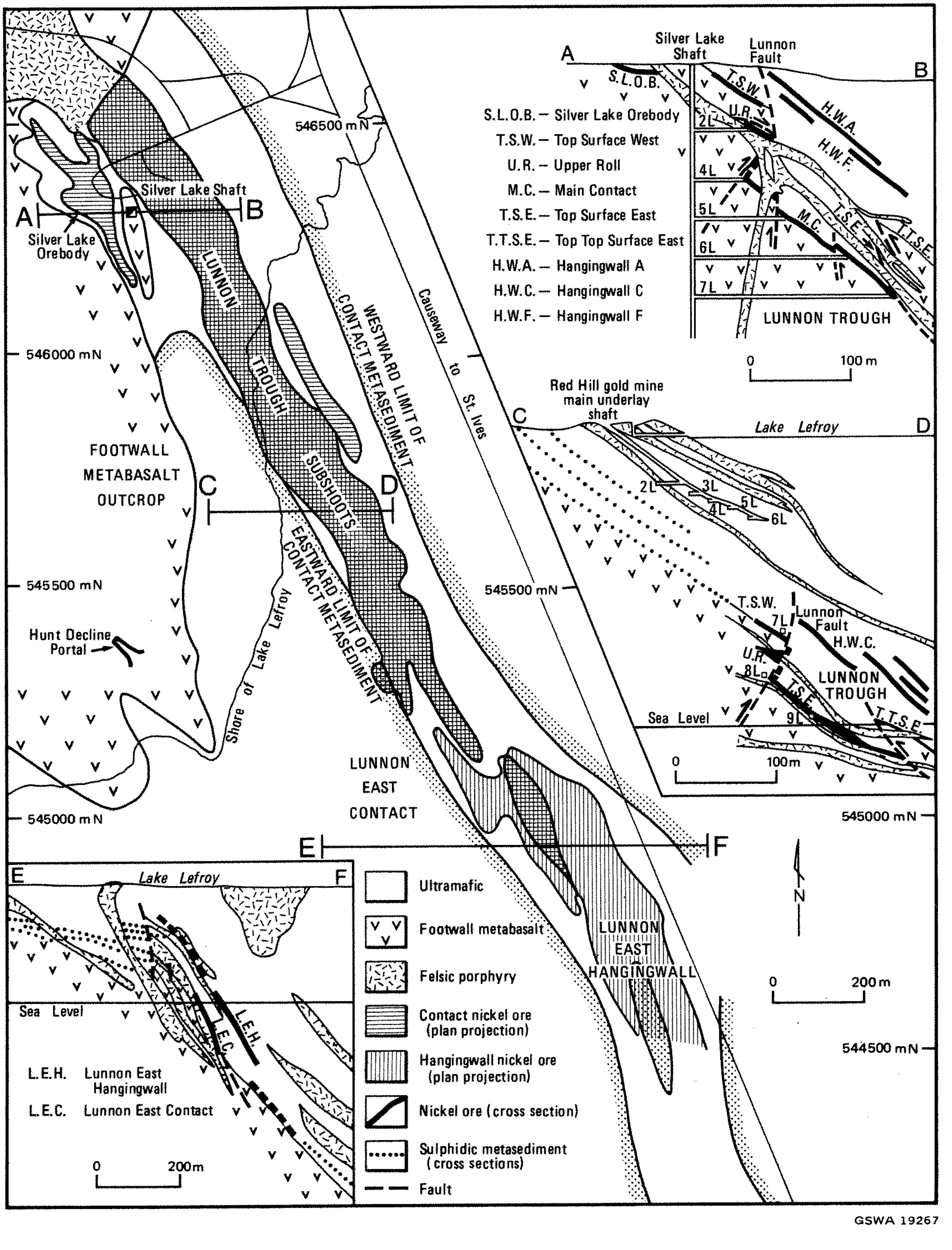

Figure 41. Geological plan and cross sections of Lunnon shoot.

Pillowed zones occur and massive iron-nickel sulphides occur between pillows in some places (e.g. 226 stope). Quartz veins occur locally.

Acid to intermediate intrusives are common and display chloritic metasomatic reaction zones where in contact with ultramafic rock.

General structure

The shoot occurs in two structural environments: Lunnon Trough in the north and the Lunnon East structure in the south.

Lunnon Trough, which contains the bulk of the nickel ore, is a trough-like depression in the footwall metabasalt-ultramafic contact and is bounded by moderate to high-angle reverse faults. The trough is 100 to 150 m wide and 1 800 m long, and plunges at about 20 degrees towards the south-southwest, except south of 545 500N where a reversal to a north-northwesterly plunge at 10 degrees occurs (Fig. 41). The floor of the trough dips eastwards at 40 to 45 degrees, and east of the trough the dip of the contact may decrease to 30 to 40 degrees. South of Lunnon Trough the dip of the shoot increases through 45 to 55 degrees, and to 75 degrees in the extreme south of Lunnon East. Here there is no faulted trough structure but a high-angle reverse fault (southern trough contact eastern shear) occurs near the western limit of the shoot and coincides with a change from steep dips in the east to gentle dips in the west (Plate 2 section IJ; Fig. 41 section EF). This fault extends northwards and terminates Lunnon Trough. In the extreme northwest of the shoot is a small, faulted or folded trough-like structure west of Lunnon Trough. This contains the Silver Lake orebody, now mined out.

The western margin of Lunnon Trough is formed by a series of vertical or steeply west-dipping reverse faults referred to as the Lunnon Fault system or main shear system. Commonly, the fault planes are curved and many contain nickel ore, or are intruded by felsic porphyries (Fig. 42). Two or more, generally east-dipping, reverse faults form the eastern margin of the trough. The most easterly and the most extensive of these faults is known as No. 2 East Thrust. Several faults strike at small angles to the trough axis and therefore cross the trough: a good example is the No. 1 East Thrust which is close to No. 2 East Thrust in the north but joins Lunnon Fault in the south (Ross and Hopkins, 1975, Fig. 22). These faults successively elevate the trough floor by means of a south-block-up component of movement.

The distribution and thickness of (i) flow units in the Kambalda ultramafic formation; and (ii) contact and hangingwall nickel ore, both imply that some of the faults in Lunnon Trough were active during ore deposition and ultramafic volcanism (Ross and Hopkins, 1975). Low-angle reverse faults such as that associated with the Upper Roll ore-bearing surface (Fig. 41, sections AB, CD) would appear to pre-date Lunnon Fault.

Ore distribution and structure

With the exception of Lunnon East Contact and Hangingwall, and Silver Lake orebody, most contact nickel ore is in Lunnon Trough and most hangingwall ore is directly above this contact ore in plan projection (Fig. 41). A little more than half the ore tonnage is present as hangingwall ore.

On the floor of Lunnon Trough, contact ore is more or less continuous for a strike length of 1 400 m. In the north this ore occurs in Main Contact subshoot (Fig. 42), which is replaced southwards by Top Surface East subshoot as No.1 East Thrust converges on Lunnon Fault. The mineralization thins southwards : matrix ore becomes dominant and porphyry intrusions become more abundant. The Upper Roll subshoot (Fig. 42) is bounded to the east by Lunnon Fault and to the west by a curving, low-angle reverse fault, and has a strike length of some 850 m from the 8 level to subcrop in the north. Top Surface West subshoot occurs up dip (west) of the trough and shows little continuity of ore except in the north. At the southern end

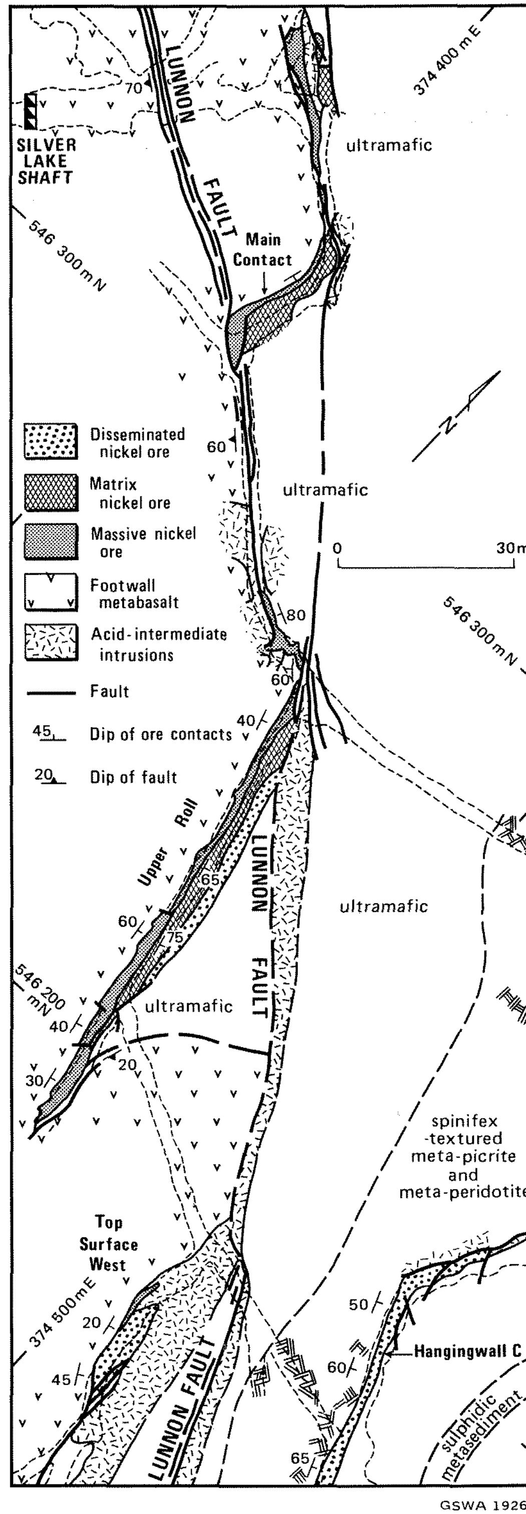

Figure 42. Geological plan of part of 4 level, Lunnon shoot showing subshoots along the western side of Lunnon Trough.

of the trough, Top Surface West locally forms a narrow subshoot which is fault-bounded to the west and east, like Upper Roll. Lunnon Fault is variably mineralized between the trough floor and Top Surface West for the entire length of the trough. The eastern faults rarely carry important mineralization, however faults which cross the trough may be well mineralized (No.1 East Thrust). Lunnon East Contact subshoot is weakly and sporadically mineralized, the better ores occurring in structurally complex areas in association with low to moderate angle reverse faults

Contact nickel ore typically comprises 0.5 to 1.5 m of massive ore overlain by 2 to 4 m of disseminated to matrix ore. Only the massive ore contains mineralogical layering and fine scale foliation. Roff and Hopkins (1975) also described the presence of a 'low-grade disseminated zone' commonly containing 3 to 4 per cent sulphides which overlies contact ore and may be up to 30 m thick. This zone is only well developed in the northernmost 800 m strike length of the shoot, and it does not constitute ore as nickel grades are generally less than 0.6 per cent. In the lower levels of the mine, which exploit the southern part of the Lunnon Trough, massive ore is best developed in and adjacent to reverse faults (comparable to Durkin shoot) and marginal to porphyry intrusions. Such massive ore is, however, variable in thickness and commonly has irregular contacts with footwall metabasalt, disseminated-matrix ore or ultramafic rocks (Fig. 43A). It may contain deformed mineralogical layering of pyrrhotite-pentlandite, lenses of fine-grained pyrite, coarse-grained pyrite idioblasts (Fig. 89A) and disrupted quartz veins. Underground exposures are now very limited but contact ore in the northern part of the trough appears to be more uniform in thickness and internal structure (Fig. 42). An example from the 4 level is described by Ewers and Hudson (1972).

In general the hangingwall ores are thinner and less affected by faulting, compared with the contact ores. The faults marginal to the Lunnon Trough have a smaller apparent displacement compared with that measurable by the displacement of contact ore. Hangingwall ore is commonly found at the base of the first flow unit above the basal unit of the Kambalda ultramafic which generally places it within 100 m of the footwall metabasalt-ultramafic contact. Only one orebody (Hangingwall B) occurs at the base of the second unit above the basal unit. Hangingwall ore may rest directly upon spinifex-textured talc-chlorite-amphibole rocks (Fig. 91B) or upon fine-grained talc-chlorite rock. Disseminated or blebby ore is commonest and is up to 2 m thick. The host talc-carbonate rock is coarser grained than the adjacent ultramafic rock. Massive ore is sparse over Lunnon Trough but where it is present it commonly overlies coarse spinifex-textured talc-chlorite in which the matrix to the coarse silicate plates in the topmost 10 to 20 cm is formed by iron-nickel-copper sulphides (e,g, Hangingwall C subshoot in 628 stope). Massive ore is commoner in Lunnon East but it is largely foliated breccia ore 10 to 25 cm thick (Fig. 43B) which lacks mineralogical layering except where it thickens in isolated pods (e.g. Lunnon East).

Ore petrology

Primary nickel ore consists of monoclinic pyrrhotite, pentlandite, pyrite, chalcopyrite, magnetite and chromite. The pyrrhotite:pentlandite ratio for contact ore is about 2.3, whereas the ratio for hangingwall ore is closed to unity. The resulting mean nickel tenors for massive ore are about 9 per cent and 17 per cent respectively.

Contact ore is generally similar, in terms of the textures and distribution of the constituent minerals, to contact ore in Juan complex. The principal difference is the finer grain size and less distinct mineralogical layering of Lunnon ore. Lenses and veins of fine-grained pyrite are also less conspicuously developed in Lunnon ore, even in structurally complex areas. Folded mineralogical layering is rare. The opaque minerals in matrix-to-disseminated ore show static metamorphic textural intergrowth with gangue minerals. Irregular patches and veinlets of massive ore occur in some matrix ore, and in the lower levels of the mine a foliation may be present in matrix ore.

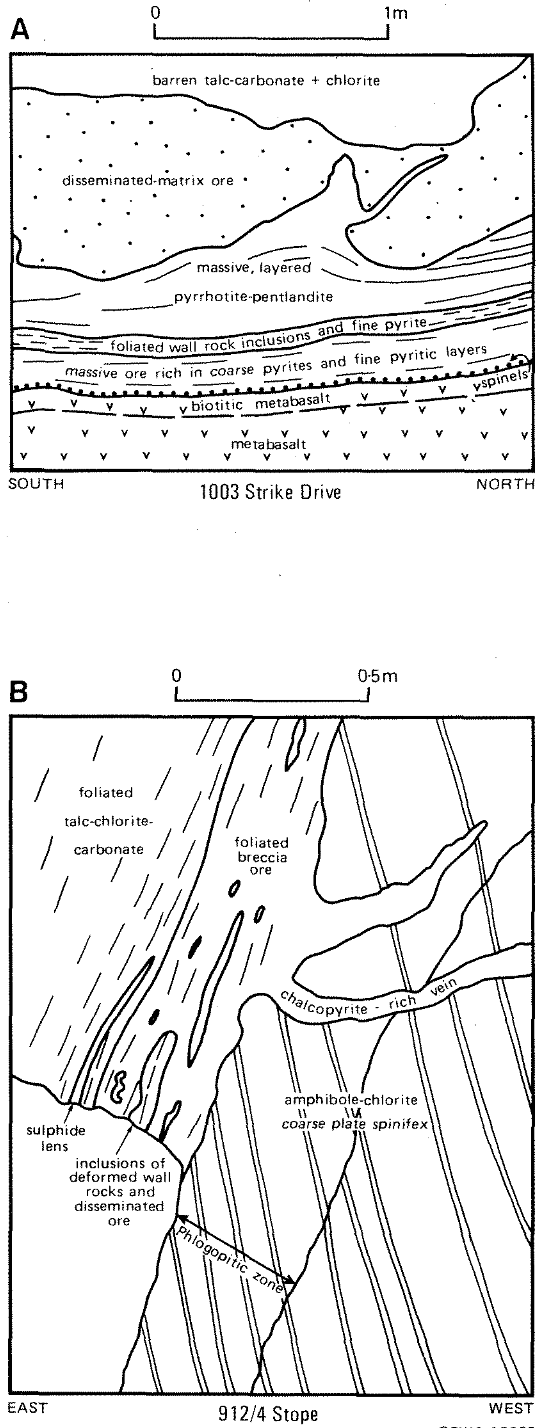

Figure 43. Sketches of vertical underground faces in Lunnon shoot. A — contact nickel ore on Top Surface East. B — hangingwall breccia ore, Lunnon East Hangingwall subshoot.

Hangingwall ore is generally pentlandite-rich, though some breccia ore from Lunnon East is pyrrhotite-rich. Blebby ore from Hangingwall A orebody consists of blebs up to 5 mm in diameter composed of the usual sulphide and spinel phases plus carbonate minerals, which occur in variable proportions from bleb to bleb. Typical blebby ore assays between 1 and 2 per cent nickel. Some of the massive hangingwall ore above Lunnon Trough is coarser grained than massive contact ore but otherwise is similar texturally. Although it is rare, the nickel ore present within spinifex-textured rock is of genetic importance. In examples from the Hangingwall C orebody in 628 stope (Fig. 91B) oriented aggregates of skeletal, zoned chromite-magnetite grains occur in the silicate spinifex plates, but are less abundant downwards and are not present below the lower limit of sulphide. The sulphides between coarse spinifex plates are, in turn, interstitial to much smaller spinifex plates (microspinifex), but sulphides and silicates are also intergrown in a fine-grained static metamorphic texture. In this case pyrrhotite (unstrained and not recrystallized into small subgrains) and lesser pentlandite, with minor pyrite and chalcopyrite, are the sulphides. The microspinifex texture is absent towards the top of the spinifex-textured sulphide ore, and chalcopyrite may be far more abundant, which is suggestive of mobilization.

A bulk composition for Lunnon shoot ore averages 12 per cent nickel (Table 31), and this composition is plotted in terms of Fe-Ni-S on Figure 34. On this diagram bulk Lunnon ore is very similar in composition to ore from Juan complex and Fisher complex.

HUNT SHOOT (31°13′15″S; 121°40′35″E)

Introduction

Hunt shoot lying on the south of Lunnon shoot on the western limb of the Kambalda dome, is in the western subgroup of deposits (Fig. 28). The shoot lacks any surface expression as it occurs below Lake Lefroy and the peninsula ('Hunt peninsular') projecting eastwards into Lake Lefroy (Fig. 28). Discovery was made by systematic diamond drilling carried out in 1970. Initially, mining took place via a crosscut from Lunnon shoot into the hangingwall ore of E Zone and the contact ore of D Zone at Hunt, and orebodies above this level were largely mined out in the period July 1974 to August 1977. Work on the Hunt decline began in June 1973, with the first ore production being realized in 1976. All mining is now carried out by diesel-powered trackless equipment using slot stoping methods of ore breaking. Development of the contact ore subshoots has followed the hangingwall ore development and seven levels are currently established, from 200 m above sea level to about 50 m below sea level.

Hunt shoot is a category 4 deposit in terms of pre-mining ore reserves. Annual production has stabilized at about 100 000 t of ore averaging 3.0 per cent nickel. In mid-1980 gold production commenced from quartz-veined shear zones in the footwall metabasalt and along the footwall metabasalt-ultramafic contact in the area of A and D subshoots.

Stratigraphy

In mineralized areas with contact ore the basal unit and member of the Kambalda ultramafic formation are generally equivalent, and are 25 to 100 m thick. The basal unit thins abruptly to the east into the axial zone of the Kambalda dome. The upper member is plagioclase-bearing in a broad zone to the southwest, which overlaps the western side of the shoot in plan projection. The shoot occurs at the northern end of the north-northwest-oriented zone of the footwall metabasalt-ultramafic contact which is free of metasediment. Two or more horizons of metasediments occur in the ultramafic rock adjacent to the shoot, and one metasediment within the ultramafic formation overlaps much of the contact ore in plan projection. All types of metasediment are present and one type commonly grades laterally or vertically into another type.

The ultramafic host is a massive or foliated, fine- to medium-grained talc-magnesite + chlorite + dolomite rock, though a small area of antigorite-bearing rocks is present in the central part of the host. The ultramafic rocks on the footwall of the hangingwall ore may be more chloritic, but are not commonly spinifex-textured. In many examples the hangingwall and footwall ultramafic rocks appear similar in underground exposures.

The footwall metabasalt is a fine-grained, dark, grey-green massive rock, which, in several places, is chloritic or biotitic within a metre of contact ore. Quartz veins are common but are truncated at the contact with overlying ore or ultramafic rock. Metabasalt involved in faulted zones may be very hard and epidotized or silicified.

Acid to intermediate intrusives are not common in mineralized areas. A thick sill-like intrusion of porphyry ("Hunt porphyry") occurs in the upper member of the Kambalda ultramafic formation overlying the E Zone Main Hangingwall subshoot. This intrusion thins abruptly westwards where it overlies the contact orebodies (Plate 2 section IJ).

General structure

The structure of that part of the shoot containing contact ore resembles Durkin shoot in some respects. Vertical to moderately southwest-dipping reverse faults disrupt the footwall metabasalt-ultramafic contact. This contact dips south-west at angles of between 10 degrees and the vertical, with 40 degrees being an average figure (Fig. 44). As a whole, the shoot plunges at about 20 degrees towards 135 degrees, a vector which is at a small angle to the axial trace of the Kambalda dome. The strike length of the shoot is some 900 m, and its maximum width is 300 m. A small fault-bounded trough-like structure is developed in the central part of the shoot, the floor of the trough coinciding with the D Zone Deeps subshoot and its margins being defined by the Q fault and Harry fault (Fig. 44). A major feature along the eastern margin of the contact subshoots is a flexure, faulted in part, which results in gentler dips to the northeast (Fig. 44, cross sections). This feature also limits hangingwall ore to the west and coincides with the westward thinning of the Hunt porphyry. The western boundary of the shoot is generally fault-controlled. The nature of the limiting structure (if any) down plunge is not yet clear.

Ore distribution and structure

Most of the contact ore and hangingwall subshoots do not coincide in plan projection (Fig. 44), and the western limit of E Zone Main Hangingwall subshoot coincides approximately with the projection of Q fault. A little more than one third of the ore tonnage is present as hangingwall ore.

From northeast to southwest the contact subshoots are known as D zone, Q fault, D zone deeps, Harry fault, F zone and A zone (Fig. 44). The best ore developments occur in A and D zones where the ore section may be 2 to 3 m thick, with the bulk of the section being massive and matrix ore. In A zone the more steeply dipping sections are poorly mineralized compared with the moderately dipping sections of the contact (Sharpe, 1978). The massive ore in A and D zones is layered mineralogically and resembles normal contact ore in Lunnon shoot, although thickness and distribution in detail are not uniform or regular, particularly in A zone. Evidence that this massive ore has been mobilized after its emplacement is provided by deformed inclusions of vein quartz (e.g. 706 stope, D zone; 801 stope, A zone).

Contact ore in the remaining surfaces generally shows more evidence of deformation. Reaction-zone breccia ore and foliated matrix-to-disseminated ore is common (Fig. 45B), and the thickness and nickel tenor of the ore section is very variable. The ore section in D zone deeps and F

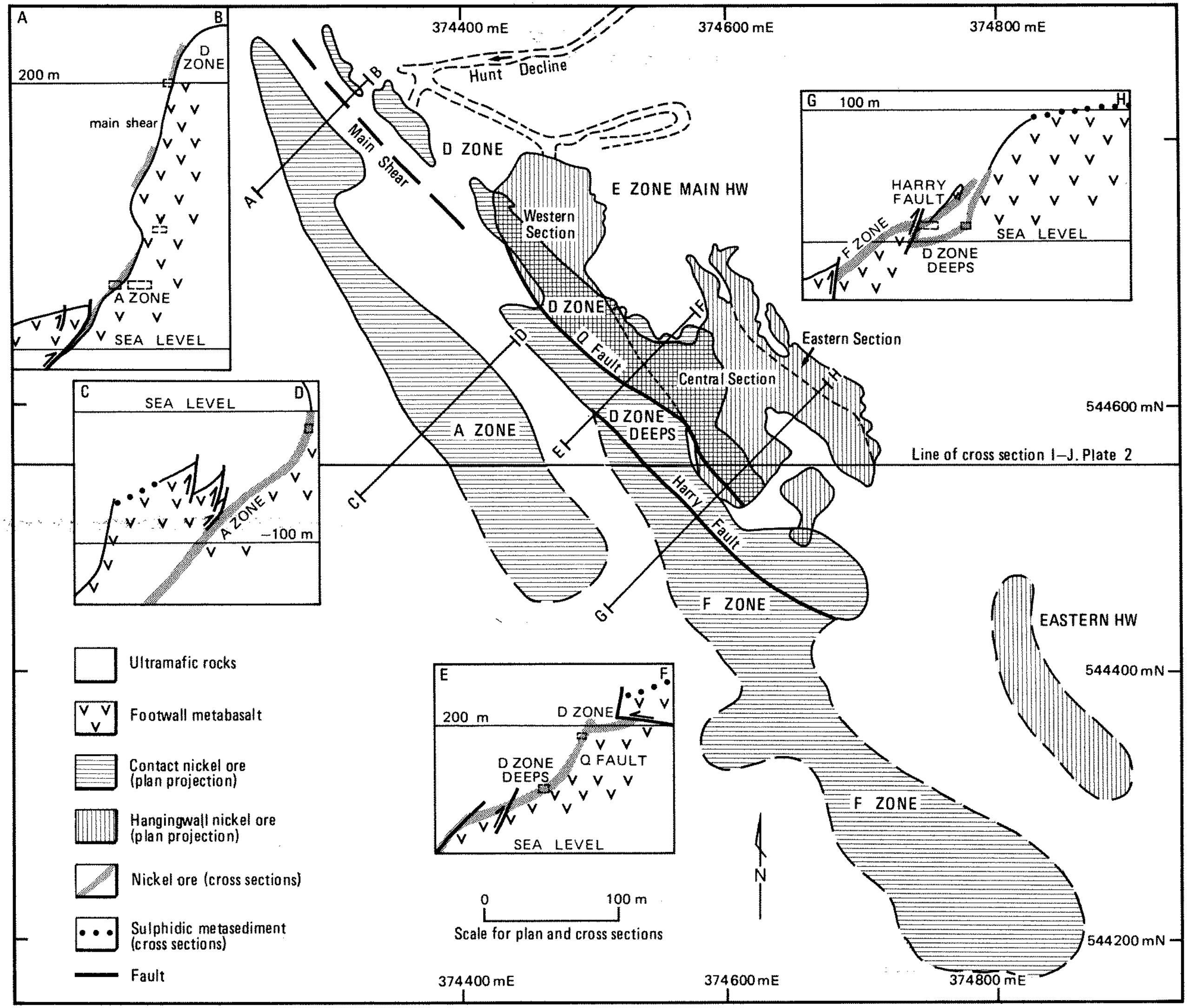

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Figure 44. Geological plan and cross sections of Hunt shoot.

zone averages 1 m in thickness (Sharpe, 1978). Layered massive ore tends to occur as thin isolated lenses which pass marginally into breccia ore (Fig. 45B). Some layered massive ore contains a second foliation oriented at an angle of about 60 degrees to the mineralogical layering and fine-scale foliation.

The history of movement on Q fault appears to be complex. Sharpe (1978) regarded the surface as a normal fault, with some reverse movement to account for the presence of offset ore in ultramafic rock (Fig. 44, cross section EF). However, he also noted that slickensides plunging at 15 degrees towards the south-southeast and displacement of D zone deeps relative to D zone, both indicate sinistral oblique strike-slip movement. An unusual feature of the southern part of D zone deeps is the presence of offset ore in a shear zone subparallel to and 5 to 20 m above the footwall metabasalt-ultramafic contact (Fig. 44, cross section GH). Apart from having strongly foliated contacts, this ore resembles a normal hangingwall ore zone (Sharpe, 1978).

The F zone subshoot appears to be structurally related to D zone deeps. The mineralization occurs in a corridor about 80 m wide of structurally disturbed contact which bears patches of ore less than 1 m thick, particularly where the footwall metabasalt is faulted over the ultramafic rock (Sharpe, 1978). Layers of massive breccia and matrix-to-disseminated ore are interleaved with barren or subgrade material.

The two hangingwall subshoots are the large E zone main hangingwall, and the smaller Eastern hangingwall, which is only known from intersections in diamond

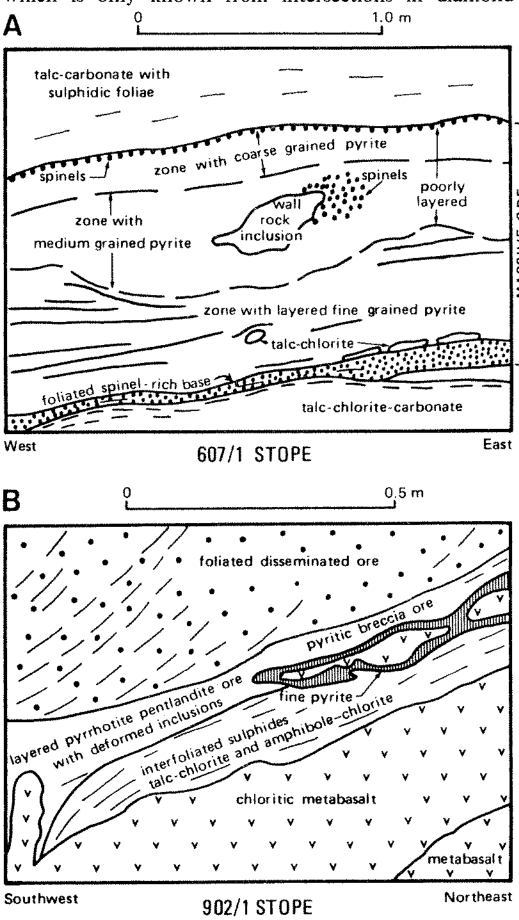

Figure 45. Sketches of vertical underground faces in Hunt shoot. A — hangingwall nickel ore in E zone Main Hangingwall orebody. B — Contact nickel ore in D Zone Deeps subshoot.

drillholes. The E zone subshoot can be divided into western, central and eastern sections (Fig. 44). The thicker and higher grade ore sections occur in the central section. The western section is lower grade and appears to be fault-bounded to the southwest. The eastern section contains more massive ore than the western section, but it is associated with sulphidic metasediment to the north and east. Here, layered chloritic metasediment with pyrite cubes 5 to 10 mm in diameter changes within 5 to 10 m into disseminated ore with similar pyrite crystals. Most E zone ore sections consist of poorly layered massive ore overlain by matrix to disseminated ore, with a total thickness of 0.5 to 2.5 m. The top and bottom contacts of the ore section are foliated and rich in spinels in many places (Fig. 45A). Some matrix or disseminated ore is foliated and contains small irregular patches of massive ore. The presence of coarse-grained pyrite dispersed throughout the ore section is a general feature which is in marked contrast to the contact ore. The weak layering in massive ore is largely defined by trains of pyrite crystals which may differ in size from layer to layer. A few large inclusions of wall rocks occur in massive ore.

The Eastern hangingwall mineralization was regarded by Sharpe (1978) as an extension of E zone, being separated from E zone by faults, sulphidic metasediment, and subgrade nickel mineralization. The western limit of the mineralization is a fault which may coincide with that bounding E zone to the west. Only five of the fourteen diamond drillhole intersections into the Eastern hangingwall contain ore-grade mineralization. This mainly consists of matrix ore with subordinate disseminated ore, plus stringers of massive sulphides.

Ore petrology

Primary nickel ore consists of monoclinic pyrrhotite pentlandite, pyrite, chalcopyrite, magnetite and chromite. Pentlandite is partly altered to violarite in most hangingwall ore. Locally melonite occurs in association with pyrite, chalcopyrite and gold in quartz veins at the footwall metabasalt-ultramafic contact in D zone. The hangingwall ores, and some ores in Q fault, D zone and F zone are pyrite-rich. Massive sulphide from contact ore typically assays about 10 per cent nickel, whereas that from hangingwall ore has a slightly higher tenor of 11 to 12 per cent. In general, matrix ore assays about 6 to 7 per cent nickel, and disseminated ore averages 2 to 4 per cent nickel.

Typical contact massive ore is similar in mineralogy, grainsize and texture to normal contact massive ore from Lunnon shoot. However, specimens of layered pyrrhotite-pentlandite ore examined are characterized by strongly foliated pyrrhotite aggregates with many kink bands and some deformation twins (Fig. 94A), and an almost total lack of pyrite. In addition the pentlandite aggregates and some chalcopyrite show physical orientation both in the main layering and fine-scale foliation, and at an angle of 40 to 60 degrees to this plane. Matrix or disseminated ore generally contains pyrite throughout.

Hangingwall massive ore, in contrast to contact massive ore, has pyrite as the major sulphide mineral, with subordinate pentlandite, pyrrhotite and chalcopyrite. Pyrite forms rounded to idioblastic grains 1 to 10 mm in diameter, the other minerals being present as a finer grained matrix with an average grainsize of less than 1 mm. Neither mineralogical layering nor a fine-scale foliation is evident in polished mounts. Zoned chromite-magnetite grains up to 2 mm in diameter, and smaller magnetite grains, are dispersed throughout the sulphides.

FISHER COMPLEX (31°12′00″S; 121°39′10″E)

Introduction

The Fisher complex of shoots occurs immediately west of the Kambalda East township on the western limb of the Kambalda dome. The gossanous expression of

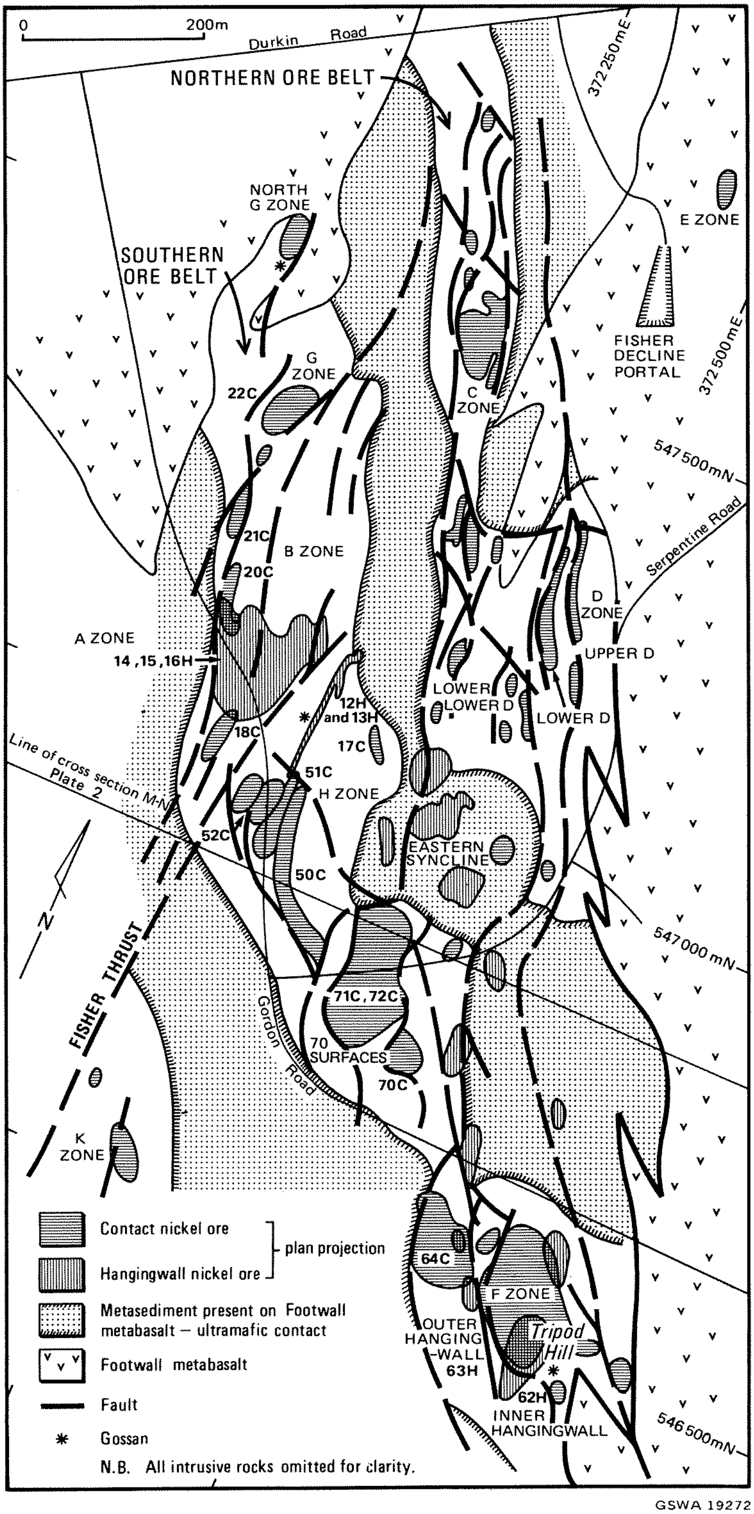

Figure 46. Geological plan of Fisher complex showing subshoots in the southern and northern ore belts (from Hancock, 1978).

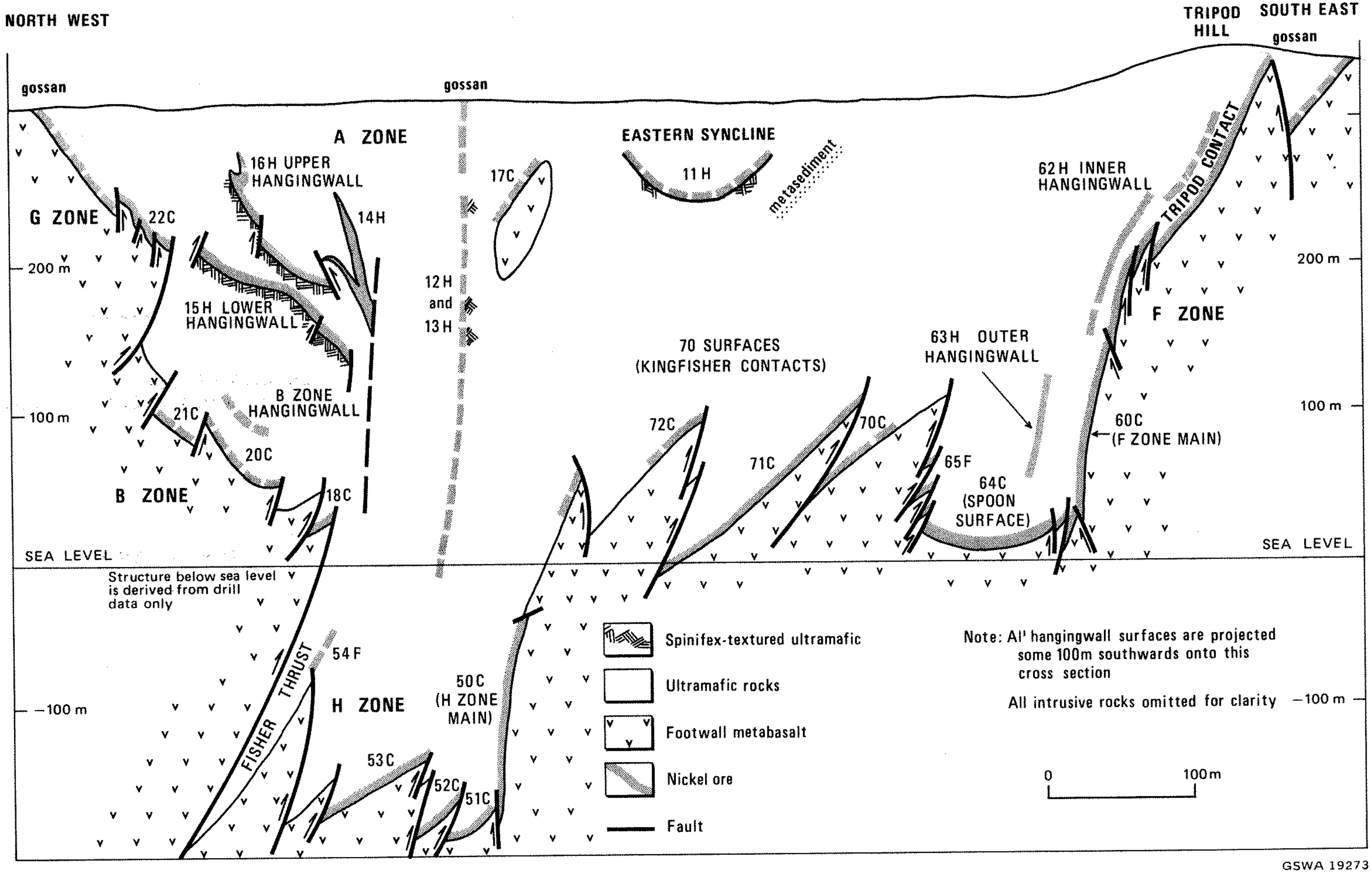

Figure 47. Diagrammatic longitudinal section through the southern ore belt, Fisher complex, showing Fisher syncline and relationships between subshoots (from Hancock, 1978).

mineralization at Tripod Hill in the extreme south of the complex (Figs 46 and 47) was discovered during the initial surveys in 1965, and the other gossans were found later. Driving of the Fisher decline began in 1971. Production of ore commenced in late 1972 and continued until late 1977 when the mine was placed on a care and maintenance basis. Production resumed in July 1979. Development of the mine has proceeded on seven levels with the deepest workings being at about sea level, which is a little more than 300 m below the surface.

Based on pre-mining ore reserves Fisher complex is a category 3 deposit.

Stratigraphy

The basal unit of the Kambalda ultramafic formation varies in thickness from 25 to 200 m, being thickest in the central part of the complex (Plate 2, cross section MN). The basal member may be several times thicker than the basal unit. The contact mineralization in the southern and northern ore belts of Fisher complex is separated and flanked by corridors of footwall metabasalt-ultramafic contact which bears sulphidic metasediment (Fig. 46). Several metasedimentary horizons occur within the ultramafic unit in the northern part of the complex.

The ultramafic host consists of mainly undeformed talc-magnesite-chlorite rock or antigorite serpentinite with variable amounts of talc and porphyroblastic carbonate minerals. The footwall metabasalt is fine grained and is not foliated except in some places at the contact with overlying ultramafic rock or nickel ore. Felsic porphyritic intrusions are abundant, particularly in the footwall metabasalt and near the contact with the ultramafic unit. In general these intrusions are less numerous from north to south. Where emplaced into ultramafic rocks the intrusions have chloritic margins or metasomatic origin. Intrusions are commonly deformed or ruptured where they occur at or on the zone footwall metabasalt-ultramafic contact (e.g. F Zone).

General structure

Fisher complex occurs in the north-trending Fisher syncline (also known as the Fisher Trough), an intensely faulted structure which plunges gently southwards and also becomes more open in that direction. The Fisher syncline is probably related to the Otter syncline, which occurs along strike to the north. The complex is divisible into a southern ore belt 1 400 m long, and a northern ore belt some 850 m long; both belts strike north-northwest (Fig. 46). The southern ore belt crosses the axis of the Fisher syncline and includes west- and east-dipping contact nickel ores (Fig. 47). The western limb of the syncline is involved in the 'Fisher thrust', a name given to a series of north-striking high-angle reverse faults which generally dip steeply westwards (Plate 2, section MN; Fig. 47). High-angle reverse faults also affect the eastern limb of the syncline. The core of the syncline is complicated by (a) narrow wedges of footwall metabasalt which have been folded and faulted up into the ultramafic rock; and (b) subordinate synclinical folds in the ultramafic unit, some of which are not congruent with the main axis of the syncline.

Ore distribution and structure

The major feature of the complex is the large number of small subshoots which make up the ore belts (Fig. 46). The structural complexity of ore distribution surpasses that of any other shoot at Kambalda. Hangingwall ore originally accounted for some 43 per cent of the total ore tonnage but the present distribution pattern shows little correspondence between hangingwall ore and contact ore when viewed in plan projection (Fig. 46). A structural study by Hancock (1978) represented a major advance in understanding ore distribution, and this study indicated that most hangingwall ore did overlie contact ore before deformation took place. Hangingwall ore in original position is mainly restricted to the southern ore belt.

In the southern ore belt contact ore is best developed in the south, in F zone. Here massive ore up to 1 m thick may be overlain by 1 to 3 m of matrix-to-disseminated ore, but such a simple ore section is uncommon. Deformation in the ore zone has resulted in the presence of irregular layers and lenses of massive ore, reaction zone breccia ore and matrix ore at various levels within less sulphidic ore, which itself may be strongly foliated (Fig. 48). Felsic porphyry sills have been intruded parallel to the ore section, and dykes are commonly truncated where they meet the ore section (Fig. 48). The 64C or 'spoon surface' contact ore is in faulted juxtaposition with F zone to the west. The ore section is 1.5 to 7 m thick and consists mainly of matrix and sulphide-rich disseminated ore, underlain by about 0.3 m of sulphide-poor disseminated ore which in turn is underlain by thin, impersistent massive and stringer sulphides (Hancock, 1978). The ore sections in the 70 subshoot are similar to F zone, though matrix ore is less common. Thick sections of layered massive ore with abundant lenses of fine-grained pyrite may occur on the faulted margins of ore-bearing surfaces where metabasalt is on both sides of ore. Porphyry dykes are truncated at the ore section. The mineralization of H zone is dominantly matrix ore with a persistent, thin basal layer of massive ore (Hancock, 1978). The B and G zone contact ore is of small extent and patchy in development.

The hangingwall ores in the southern ore belt occur at contacts between ultramafic flow units (11H, 13H, 14H, 15H, 16H, 62H subshoots), or as zones of blebby sulphides within ultramafic units (B zone hangingwall and 63H). The subshoots are described from south to north, with most information being drawn from Hancock (1978). The 62H subshoot dips parallel to the F zone contact and consists of strongly foliated disseminated ore and stringer sulphides which abut pyrrhotitic metasediments (marginally nickeliferous) to the south. The 63H subshoot is an irregular zone of discontinuous blebby milleritic sulphides, with local patches of sulphide-poor disseminated ore and sulphide stringers. Hangingwall ore in the 11H or 'Eastern syncline zone' is a complexly folded south-plunging horizon of blebby and disseminated to matrix, supergene and transitional sulphides. A spinifex-textured footwall ultramafic rock is present in some areas. Tightly folded sulphidic metasediment, which is locally nickeliferous, is in contact with 11H ore to the north. The 12H and 13H subshoots, though cut by numerous small faults, constitute the most continuous zone of hangingwall ore in Fisher complex, with a strike length of 150 m and a downdip dimension of more than 300 m. The northern (12H) portion contains some massive ore which is locally injected into the top of the underlying spinifex-textured metapicrite, present to the east. The southern (13H) portion is lower grade and comprises blebby and disseminated ore which may abut sulphidic metasediments.

The remaining hangingwall ores occur west of the Fisher thrust. The 15H lower hangingwall subshoot is up to 10 m thick and consists of massive, matrix and disseminated sulphides with a gradual upwards decrease in sulphide content into barren hangingwall ultramafic rocks. Spinifex-textured metapicrite is locally present as the footwall, and here sulphide may occur interstitially to the spinifex plates. To the north the subshoot is replaced by sulphidic metasediment involved in folds which plunge to the southeast. The 14H and 16H mineralization is involved in an inclined synclinical fold (Fig. 47). Easterly dips of 30 to 60 degrees characterize the 16H orebody which is largely disseminated ore overlying a spinifex-textured ultramafic rock in the footwall. Sulphidic cherty metasediment is in contact with the nickel mineralization in the north, where gently south-plunging folds occur. A similar pyrrhotitic metasediment and chloritic metasediment are complexly infolded with lenses of pyrrhotite-rich massive ore and peridotitic to picritic ultramafic rocks (some spinifex-textured) in the steeply east-dipping 14H subshoot present in the core of the syncline.

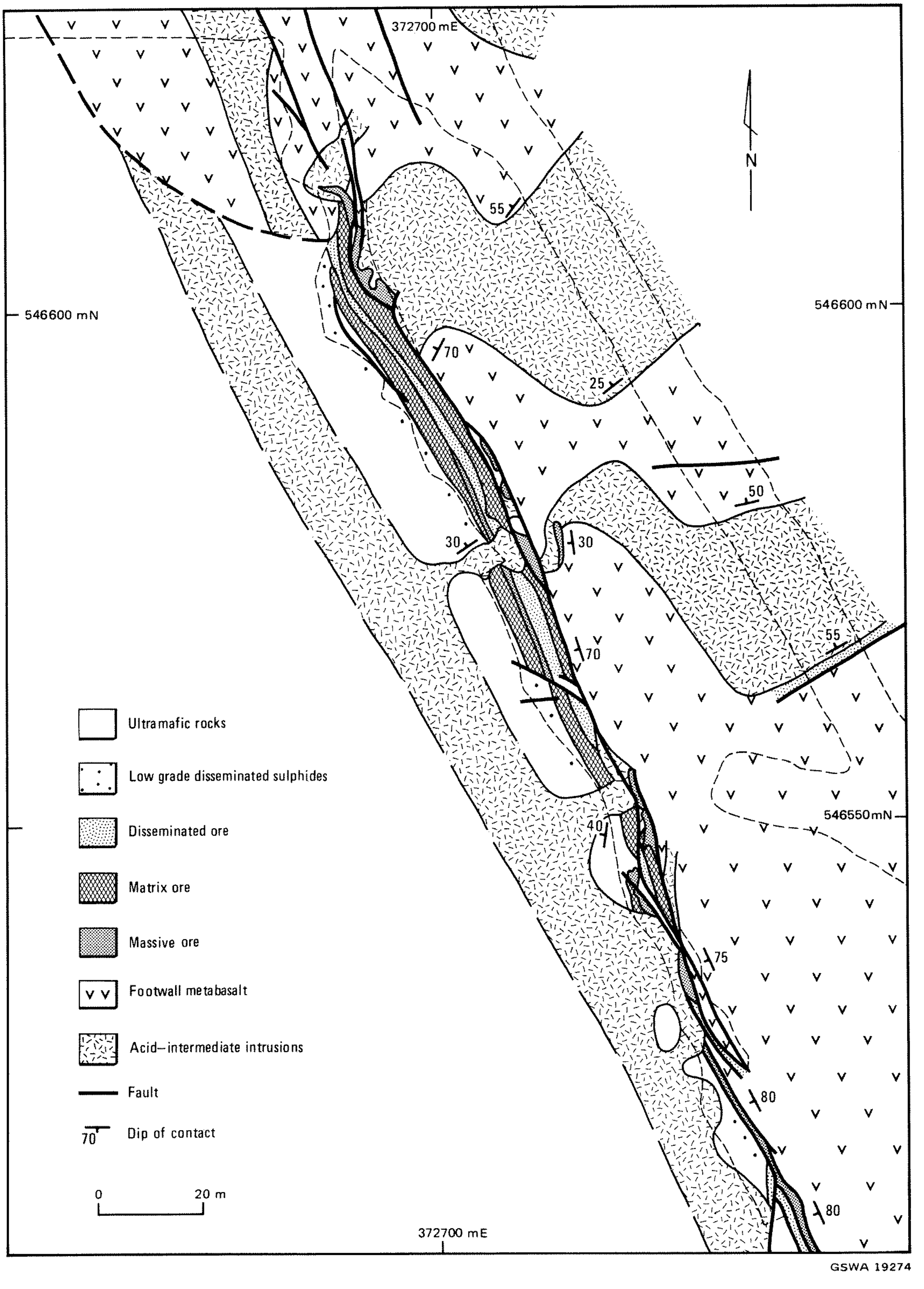

Figure 48. Geological plan of part of 6 intermediate level, Fisher complex, showing contact ore of F Zone Main (60C surface).

Nickel mineralization in the northern ore belt occurs on very deformed footwall metabasalt-ultramafic contacts and it is consequently very irregularly distributed. Massive, breccia and matrix-to-disseminated ore is present, though some ore sections are of high-nickel tenor, but variability in grade is commonplace. Dips are generally steeply westwards, and intrusive porphyries are abundant.

Ore petrology

Primary nickel ore consists of monoclinic pyrrhotite, pentlandite, pyrite, chalcopyrite, magnetite and chromite. Millerite, pyrite and magnetite occur in the blebby hangingwall ore of 63H zone. Primary iron-nickel sulphides are replaced by supergene violarite and pyrite to a depth of 40 m in disseminated ore and 60 m in massive ore. Violarite occurs in the transition zone to 120 m depth, reaching to more than 150 m in foliated massive ore of D zone. Contact massive ore from F zone typically returns assays of 8 to 11 per cent nickel, whereas matrix ore yields assays of 4 to 6 per cent nickel. In the northern part of the southern ore belt contact massive ore is lower grade and assays 7 to 9 per cent nickel. The pyrrhotite-rich massive ore of 14H subshoot assays 3 to 7 per cent nickel.

Most massive ore seems to lack a distinct mineralogical layering of pyrrhotite and pentlandite, although lenses and layers of fine-grained pyrite may be present and a fine-scale foliation is well developed. Pentlandite grains up to 2 mm in diameter form aggregates enclosed by an annealed matrix of elongate pyrrhotite crystals, which are mostly less than 0.2 mm in diameter. Kink bands are present in most pyrrhotite. Zoned chrome spinels occur throughout all ores, and are up to 3 mm in diameter. Reaction-zone breccia ore may be rich in fine-grained ovoid to rounded pyrite, but coarse pyrite seems to be rare in either breccia or massive ores.

Matrix and disseminated ore resembles that described from other shoots and contains fine-grained sulphide minerals. Some matrix ore has a static metamorphic intergrowth texture developed between sulphides and gangue. Carbonate porphyroblasts contain numerous globular inclusions of sulphides.

A bulk composition for Fisher complex ore is 13.7 per cent nickel (Table 31), and this composition plots very close to the position of bulk samples from Lunnon shoot and Juan complex on an Fe-Ni-S system diagram (Fig. 34). Fisher complex ore is also comparatively rich in precious metals, particularly gold (Table 31). This high value partly results from the inclusion of auriferous material from carbonate-quartz veins which are closely associated with nickel ore sections especially the hangingwall 13H subshoots (Schmulian, 1975). Some gold-bearing veins appears to be preferentially located near boundaries between antigorite serpentite and talc-carbonate rocks. Selective mining of high-grade specimen stone in the early history of the mine yielded after treatment some 30 kg of gold from 2 t of ore (Schmulian, 1975).

KEN SHOOT (31°10′50″S; 121°38′00″E)

Introduction

Ken shoot is 2.5 km northwest of Fisher complex, and is again on the western limb of the Kambalda dome. With McMahon, Gellatly, Gordon, Wroth and Loreto shoots, Ken shoot forms a cluster of small deposits, known as the 'Northwest Flank orebodies' or the 'McMahon complex', which lie in the western subgroup of deposits (Fig. 28).

The shoot has no surface expression and it was discovered in late 1971 by widely spaced diamond drilling of the Kambalda ultramafic formation. Access is provided by the McMahon decline via a 900 m long drive to the southwest, and the mine is developed on six main levels, from a subsidiary decline, to a depth of about 60 m above sea level. The decline was begun in 1971 and ore production was achieved in late 1972. Ken shoot is a category 4 deposit in terms of pre-mining ore reserves.

Stratigraphy

The basal unit of the Kambalda ultramafic formation is generally equivalent to the basal member. It is only 10 to 50 m thick in much of the mineralized area, but it thickens to 100 m on the western margin of the shoot. Metasediment occurs on the footwall metabasalt-ultramafic contact and within the ultramafic formation in the northern part of the shoot. In one area metasediment on the contact oversteps, on both sides, a depression in the contact which contains nickel ore and the basal unit.

The ultramafic host is a talc-magnesite plus chlorite rock which is commonly foliated in the ore zone. The basal few metres of the ultramafic unit may be of periodotitic composition (i.e. talc-chlorite). Plagioclase-bearing ultramafic rock occurs in the upper member of the Kambalda ultramafic formation down dip from the shoot. The footwall metabasalt is a dark green-grey rock or is pale grey where more felsic or epidotized. Pillowed zones are common, especially in the upper levels of the mine. Pillow margins may be picked out by a rim that is more felsic and lacks hornblende prisms, or by a rim that is more mafic and is rich in hornblende prisms. Interpillow material is generally more mafic than the pillows. Again in the upper levels of the mine, massive iron-nickel-copper sulphides may be present in interpillow spaces in metabasalt either at the basal contact with the contact ore section, or at lower stratigraphic levels within the metabasalt. Contact relationships between footwall metabasalt, and basal member and contact nickel ore suggest that the contact surface is complex and partly represents the top of a pile of overlapping, volumetrically small basalt flows (see later).

Felsic porphyry intrusions are an important feature of the lower levels of the mine, where sill-like bodies up to 35 m thick cut across the ore section.

General structure

In plan projection the shoot has a long axis which is 400 m and is oriented north-northwest, parallel to the axial trace of the Kambalda dome. Normal to this direction, mineralization extends downdip to some 350 m. Dips are in the range 25 to 65 degrees, except for the upper-most part of the shoot which is sub-horizontal (Fig. 49). The shoot also plunges gently to the north-northwest.

Several aspects of the general structure of Ken shoot (Fig. 49) are comparable with Durkin and Hunt shoots. The footwall metabasalt-ultramafic contact is disrupted by high and low-angle reverse faults, most of which dip westwards. Some pronounced inflexion structures in the contact seem to be original depressions in the volcanic surface. Deep ore-bearing trough-like fault structures are not developed: Ken Lower Trough is shallow and only contains a small proportion of the ore reserve. Major folds are absent but the flattening of dips in the uppermost part of the shoot resembles the effects of the major flexural fold at Hunt shoot. The limits to Ken shoot, both up and down dip, are apparently defined by faults, with the exception of the western sediment mineralization. Metasediment occurs on some of the contact along strike to the north, and porphyry intrusions obscure much of the contact at the southern end of the shoot.

Ore distribution and structure

Hangingwall ore is sparse, accounting for only 6 per cent of the total ore tonnage, and it is restricted to the northern margin of the shoot where it overlies sulphidic metasediment.

Contact ore occurs in thirteen subshoots which are named on Figure 49. Most contact ore consists of massive and/or disseminated ore; matrix ore is uncommon. Ken Main (Fig. 50A) and Ken Lower Trough subshoots are the largest, but in both bodies massive ore mainly occurs as thin, short lenses. Disseminated ore, though more extensive, is generally of low grade. Ken Main ore is strongly foliated.

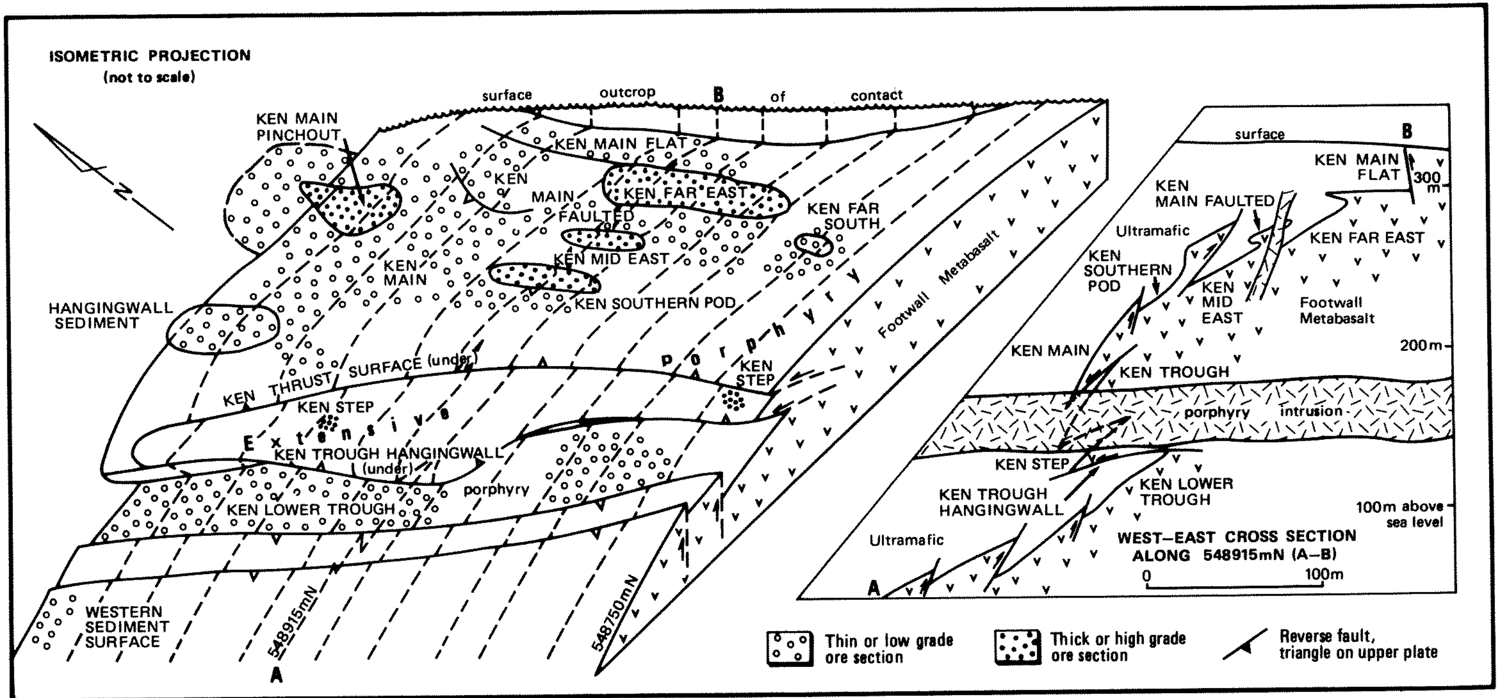

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Figure 49. Isometric projection looking northeast of Ken shoot showing the footwall metabasalt-ultramafic contact, major reverse faults and the general distribution of ore (from Anderson, 1977).

The thickest and most extensive developments of massive ore are found (i) in embayments (depressions) in the footwall metabasalt-ultramafic contact (e.g. Ken Main Pinchout, Ken Lower trough, Ken Mid East, Ken Far East, Ken Southern pod); (ii) where the ultramafic rock is faulted out against the footwall metabasalt by a low-angle reverse fault (e.g. Ken thrust surface); and (iii) marginal to porphyry intrusions (Ken step).

Massive and overlying disseminated ore in embayments accounts for the major part of the total mineralization in the shoot. The massive ore contains coarse mineralogical layering, fine-grained pyrite lenses and a fine-scale foliation. These embayments are oval in plan projection (Fig. 49), are up to 160 m long and 20 m deep, and contain up to 2 m of massive ore overlain by 2 m of disseminated ore (e.g. Ken Mid East, Fig. 50A). The margins of these embayments are probably not fault controlled, although some movement parallel to the basalt-ultramafic contact may have occurred locally. Reeve (1975) and Anderson (1977) interpreted these embayments as the product of reverse faulting around the entire perimeter of the structure, a phenomenon referred to as "cone thrusting". Such a mechanism seems theoretically unlikely and no evidence could be found in the mine for such movement having occurred. Contacts between the ore and footwall metabasalt at the edges of embayments, though abrupt, seem more likely to be the result of the ore-bearing ultramafic lava flow, or a massive sulphide flow alone, being contained as a pond in the topographic depression in the basalt surface (Fig. 50B).

Further evidence that these embayments are of topographic origin is provided by the continuity of a sulphidic metasedimentary horizon from Ken Main subshoot in the east to the same contact to the west of the Ken Main Pinchout subshoot (Reeve, 1975). Therefore the horizon occurs at the footwall metabasalt-ultramafic contact either side of the embayment, but caps the basal unit and its contact nickel ore in Ken Main Pinchout.

Ore petrology

Primary nickel ore consists of monoclinic pyrrhotite, pentlandite, pyrite and chalcopyrite, with minor or accessory magnetite, chromite and gersdorffite. Pentlandite is partly altered to violarite in contact ore from the uppermost parts of the mine, though co-existing massive sulphides in the interpillow spaces of footwall metabasalt may not be altered. In massive ore variable pyrrhotite:pentlandite ratios result in assays varying from 8 to 19 per cent nickel. Pyrite is the dominant iron sulphide phase in some places and it tends to be more abundant in disseminated versus massive ore. A composite sample of interpillow massive sulphide from footwall metabasalt southeast of Ken Far East (sample locality on Fig. 50) assayed 10.7 per cent nickel. Lenses of fine-grained pyrite occur in this massive sulphide and in the main ore zones. A bulk composition for Ken shoot ore contains 15.0 per cent nickel, and has a high arsenic content of 131 ppm (Tables 30 and 31).

McMAHON SHOOT (31°10′10″S; 121°37′50″E)

Introduction

McMahon shoot is 1.3 km north-northwest of Ken shoot, at the northwestern limit of the footwall metabasalt which crops out in the core of the Kambalda dome (Fig. 28). The shoot is in the central part of the McMahon complex which also includes Gellatly, Gordon, Wroth, Loreto and Ken shoots.

The shoot has no surface expression but was discovered in 1968 by widely spaced diamond drilling of the Kambalda ultramafic formation. Access is provided by the McMahon decline, the portal of which is 1 km to the southeast. The mine is developed from the 2, 3 and 4 levels (development of a fifth level is underway) equivalent to a vertical interval from 160 to about 230 m above sea level. The decline was begun in 1971 and ore production was achieved in late 1972. The McMahon Hangingwall part of the shoot is a category 4 deposit in terms of pre-mining ore reserves. Recoverable reserves are only about one third of this figure because of bad ground conditions, and the large amount of metasediment associated with the ore. Additional mineralization occurs in the McMahon Deeps part of the shoot which is known only from diamond drilling intersections. This part is also a category 4 deposit.

Stratigraphy

The basal unit of the Kambalda ultramafic formation is less than 50 m thick in the area of McMahon Hangingwall orebody, but is up to 150 m thick over the McMahon Deeps contact mineralization to the northwest. Metasediment is present on the footwall metabasalt-ultramafic contact in the northern part of McMahon Deeps, but metasediment within the ultramafic rock is mainly absent above McMahon Deeps. However, elsewhere in the shoot between one and three metasedimentary beds occur within the ultramafic formation. Sulphidic cherty metasediments are dominant, but locally these grade laterally or vertically into chloritic types.

The ultramafic host is foliated talc-dolomite-chlorite for the hangingwall ore, with more magnesian types such as talc-magnesite + chlorite being associated with the contact mineralization. Some ultramafic rocks in the ore zone are phlogopitic. The footwall metabasalt is fine- to medium-grained and generally undeformed. Intrusive rocks are uncommon.

General structure

The shoot is divisible into two main parts which are (i) an upper part called the McMahon Hangingwall subshoot measuring 350 m by 170 m in plan projection; and (ii) a lower part called the McMahon Deeps mineralization which consists of several small occurrences in an area measuring 600 m by 100 m in plan projection. The long axes of both parts of the shoot strike north-northwest, and there is no overlap between the parts in plan projection. McMahon Deeps occurs down dip, and to the north, of McMahon Hangingwall (Fig. 28; Plate 2, Section GH). The shoot dips westwards at angles of between 35 and 55 degrees. Steeply west-dipping reverse faults are characteristic of McMahon Hangingwall (Fig. 51B), and both west- and east-dipping reverse faults occur in McMahon Deeps and define a narrow trough-like structure known as McMahon Deeps trough (Plate 2, section GH).

McMahon Hangingwall subshoot is limited up dip by a high-angle reverse fault known as Eastern shear (Fig. 51B). Down dip and along strike the orebody is confined by sulphidic metasediment. McMahon Deeps mineralization is confined structurally or by sulphidic metasediment, except in the south where the mineralization simply dies out.

Ore distribution and structure

McMahon Hangingwall is composed entirely of hangingwall ore, whereas McMahon Deeps consists mainly of contact mineralization plus minor (less than 10 per cent) hangingwall mineralization.

The base of the McMahon Hangingwall subshoot is 25 to 35 m above the footwall metabasalt-ultramafic contact (which carries a sulphidic metasediment). Nickel ore is interleaved with, or in contact with, sulphidic metasediment throughout 60 per cent of the area of the orebody. Commonly the metasediment forms the footwall to the ore (Fig. 51C). Bavinton (1979) reported that nickel ore may be regularly interbedded with this metasediment. The ore and the metasediment occur in a strongly deformed zone, in which their thicknesses change abruptly along strike or in the dip direction (Fig. 51A). In general then, the mineralization is stratigraphically controlled, but in the upper mine workings (mainly above 2 level) thin (less than 0.5 m) sheets of ore occur in high-angle reverse faults

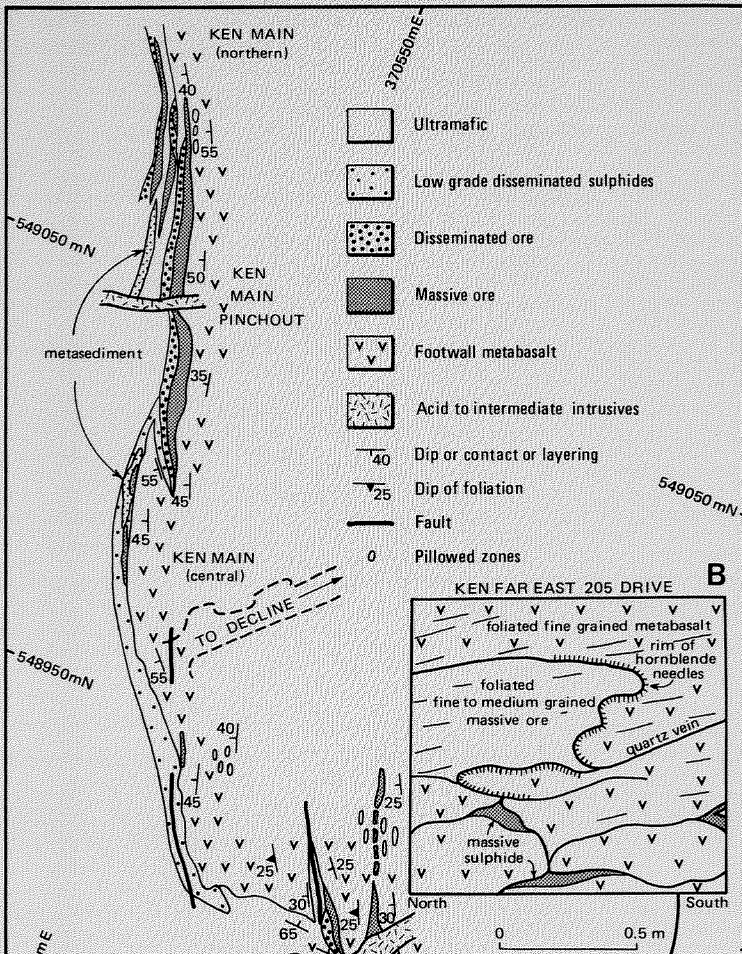

Figure 50. A. Geological plan of 2 Level, Ken shoot showing distribution of contact ore and embayments in the footwall metabasalt-ultramafic contact.
B. Sketch of vertical underground face at southern extremity of Ken Far East subshoot. Pillowed footwall metabasalt occurs above, below, and adjacent to, massive ore. Massive nickel sulphides also occur between pillows.

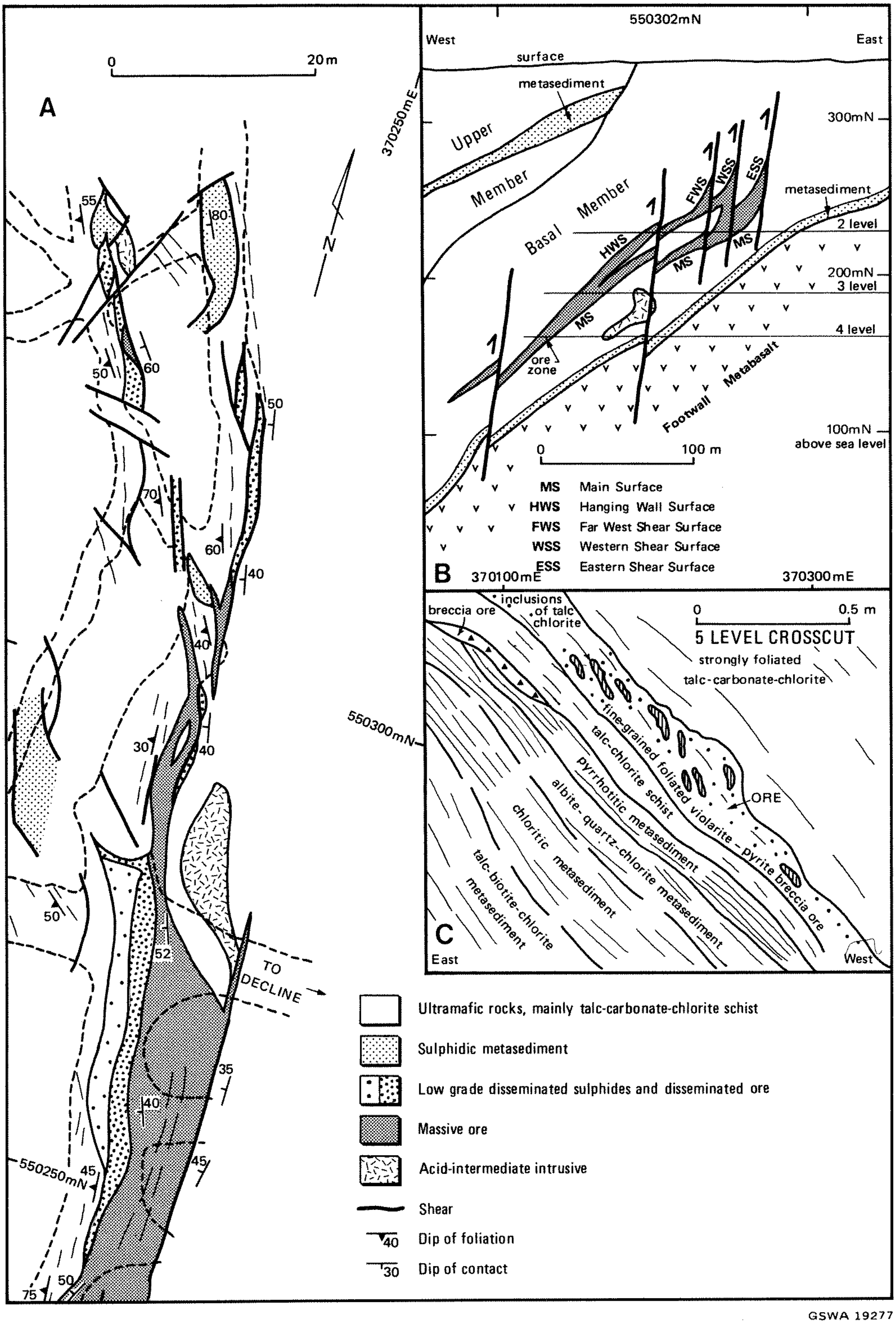

Figure 51. A. Geological plan of central part of 2 level, McMahon Hangingwall subshoot showing irregular distribution of nickel ore and metasediment.
B. Cross section through McMahon Hangingwall subshoot at 550 301 N (from Anderson, 1977).
C. Sketch of vertical underground face in 5 level cross-cut through McMahon Hangingwall subshoot, here with a metasedimentary footwall.

(Eastern, Western and Far Western shears, Fig. 51B). Furthermore in the central part of the shoot, the ore bifurcates and occurs at two levels as Main Surface and Hangingwall orebodies. The ore section is thickest and least disturbed in the middle section of 2 level where 5 m of massive ore is overlain by 1 m of disseminated ore which passes up into 1.5 m of low-grade disseminated ore (Fig. 51A). Elsewhere the ore section is generally less than 1.5 m thick and consists of irregular bodies of foliated breccia ore (Fig. 51C), disseminated or veinlet sulphides. The margins of the ore section are commonly tectonic, and the foliation in the enclosing talc-carbonate-chlorite rocks is oblique to, or curves into sub-parallelism with the top and bottom contacts of ore.

For McMahon Deeps, Anderson (1977) has interpreted five possible 'subshoots', all of which are patchily mineralized. McMahon Deeps trough subshoot occurs centrally, but only appears to be well mineralized in the south where contact ore sections 2 to 4.4 m thick and averaging about 4.5 per cent nickel have been drilled. East Flank Contact and East Flank Hangingwall subshoots are up dip of McMahon Deeps trough. They consist largely of disseminated or veinlet sulphides with minor low-tenor massive sulphides which may be interleaved with, and/or contain, inclusions of pyrrhotitic cherty metasediment. The best intersection through these two subshoots averages 3.07 per cent nickel over 3.34 m drilled width (KD 9138). Western Sediment Contact subshoot and Far West Contact are both down dip of McMahon Deeps trough, and again consist largely of disseminated sulphides with the best intersection being 6.03 m averaging 2.31 per cent nickel (KD 9147).

Ore petrology

Nickel ore in McMahon Hangingwall is altered to a supergene assemblage of pyrite and violarite plus minor to accessory amounts of chalcopyrite, marcasite, magnetite (primary and as secondary veins), chromite and gersdorffite. Massive sulphides typically assay between 7 and 12 per cent nickel.

McMahon Deeps contains primary ore made up of monoclinic pyrrhotite and pentlandite, plus pyrite, chalcopyrite and spinels. According to Nevill and Randell (1975) massive ore on normal contacts contains about 10 per cent nickel, whereas that adjacent to metasediment is more pyrrhotite-rich and assays about 5 per cent nickel, but massive ore in shears may be high grade (up to 20 per cent nickel). Metasediment adjacent to nickel ore contains minor amounts of pentlandite dispersed in pyrrhotite, but chromite and magnetite are conspicuously absent from the sulphide layers. Even though pyrrhotite layers cut across the bedding in metasediments and eventually form breccia sulphides containing deformed silicate inclusions, the presence of pentlandite in the absence of chrome spinel suggests that nickel migration into the metasediment was by diffusion rather than by physical mobilization.

A bulk composition for McMahon Hangingwall ore shows 12.0 per cent nickel. It has high arsenic and zinc contents of 154 ppm and 183 ppm respectively (Tables 30 and 31).

GELLATLY AND WROTH SHOOTS

Introduction

Gellatly shoot (31°09′50″S; 121°37′55″E) is 1 to 1.7 km north of the McMahon decline portal, whereas Wroth shoot is 2 km north of the portal. Both shoots are at the northern end of the McMahon complex.

Gellatly shoot was discovered in 1968 during percussion drilling sited around gossanous float to the east of McMahon Hangingwall orebody. Wroth shoot has no surface expression but was found by traverse diamond drilling in 1970. Access to both shoots is provided by crosscuts from the McMahon decline. Development at Gellatly shoot has taken place on seven levels ranging from 55 to 285 m above sea level, and two levels have been estabished in Wroth shoot. The combined pre-mining ore reserve of the shoots defines them as a category 5 deposit. Production is now mainly from Wroth shoot as the bulk of Gellatly shoot has been mined out.

Stratigraphy

The basal unit of the basal member of the Kambalda ultramafic formation is less than 50 m thick, except in parts of the southern section of Gellatly shoot where it may be 100 m or more in thickness. The basal member is more than 100 m thick except for the northern tip of Gellatly shoot. At Wroth shoot the member is less than 25 m thick. Metasediment is present on the footwall metabasalt-ultramafic contact immediately to the east and northwest of Gellatly shoot and to the west of Wroth shoot, but it is absent elsewhere. Metasediment occurs within the ultramafic rock overlying most of Gellatly shoot but it is not present to the east, north and south. Cherty and chloritic metasedimentary types are found.

The ultramafic host at Gellatly is an undeformed medium-grained talc-carbonate + chlorite rock characterized by magnesite porphyoblasts up to 10 mm diameter in its lower part. Veins of medium- to coarse-grained carbonate minerals cut the ultramafic but do not transect massive ore. In addition to this rock type, spinifex-textured talc-chlorite-carbonate and coarse-grained amphibole-chlorite rock with a static metamorphic texture are associated with Wroth shoot. These rocks may be foliated. The footwall metabasalt is dark, fine grained and undeformed. Metasomatic reaction-zone material consisting of medium-grained amphibole, biotite and chlorite is common at the contact with overlying ore or ultramafic rock. Intrusive rocks are rare. although a thick west-dipping dyke of felsic porphyry occurs to the east in the western limb of the Otter syncline.

General structure

Gellatly shoot occupies a trough-like structure (Gellatly Main trough) at least 900 m long and up to 70 m wide which plunges at 25 to 30 degrees towards the north-northwest (Fig. 52). In general this trough appears to represent a synclinical box-shaped fold modified by high-angle reverse faulting in its limbs. Accordingly it is comparable with, though much smaller than, the structure occupied by Juan Main shoot. Wroth shoot seems to be contained by a still smaller, but more appressed, faulted synclinical structure (Wroth trough) which has an axial surface inclined steeply to the west, subparallel to the axial surface of the Otter syncline. Wroth shoot has a strike length of about 150 m, with an overall plunge of about 5 degrees towards the north-northwest. Both shoots occur on the western west-dipping limb of the inclined anticline immediately west of the Otter syncline (Fig. 28), with Wroth shoot situated up dip of the down plunge projection of the Gellatly trough structure.

Ore distribution and structure

Excepting some isolated and irregularly distributed thin sections of disseminated sulphides intersected in 14 diamond drillholes, nickel mineralization in Gellatly shoot is confined to the footwall metabasalt-ultramafic contact. Nickel ore occurs mainly in the open axial region of the syncline, but is also present on either the western or eastern limb (Fig. 52), and occurs locally as veinlets and weak disseminations in the faults bounding the shoot. Current development has shown that contact ore is thickest and most regularly distributed between the 2 and 6 levels. Here the ore section typically consists of a layer, 0.5 m thick, of disseminated sulphides in an undeformed talc-porphyroblastic magnesite rock, underlain by irregular layers and lenses of massive sulphides up to a few tens of centimetres thick (Fig. 52). The massive sulphides are finely layered and foliated, and include some breccia ore. Sub-grade (i.e. not economically workable at present) mineralization generally consists of

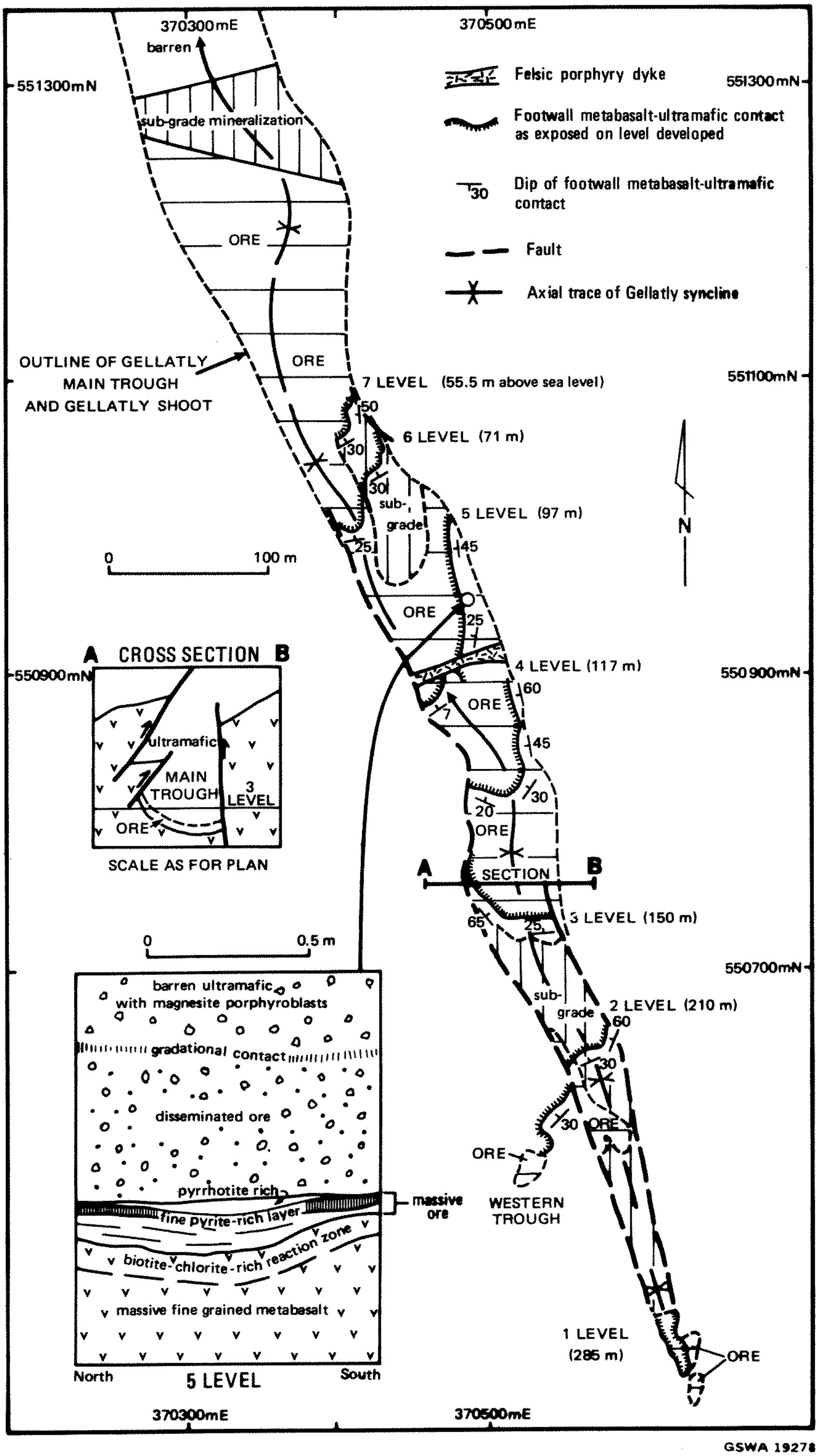

Figure 52. Composite plan and cross section of Gellatly Main trough and shoot showing levels developed and structure of shoot. Sketch of vertical underground face in 5 level illustrates a typical section through ore.

sparse, thin lenses and veinlets of massive sulphides with little or no disseminated sulphide, and is extensive above the 3 level (Fig. 52). Such mineralization also occurs at the northern termination of the shoot and as a small patch between the 7 and 5 levels. A small patch of ore occurs in the subsidiary 'western trough' structure at the southern end of the shoot.

Wroth shoot is a hangingwall orebody, although faulting along the western margin of the Wroth trough brings some ore into juxtaposition with the footwall metabasalt. Most ore occurs near the western wall of the trough in a sheared environment characterized by spinifex textured rocks, coarsely recrystallized amphibole-chlorite rocks and metasediment. The ore is commonly strongly foliated and contains boudinaged pods of country rock which may be several metres long. Massive ore occurs as lenses up to 3 m thick accompanied by disseminated-to-matrix ore or sulphide veinlets which may underlie or overlie massive ore. Disseminated sulphides also occur in lensoid bodies separate from massive ore.

Ore petrology

Supergene violarite-pyrite ore occurs on 1 level in Gellatly shoot, but at deeper levels primary assemblages of pyrrhotite-pentlandite-pyrite + chalcopyrite + spinel prevail. Massive sulphides generally assay between 10 and 12 per cent nickel, and most disseminated ore has an average content of between 3 and 5 per cent nickel. Massive ore in Wroth shoot has a similar mineralogy, but it tends to be richer in pyrrhotite and accordingly returns assays of between 7 and 8 per cent nickel.

In massive ore from both shoots pyrrhotite is fine- to medium-grained and forms well annealed aggregates of elongated, polygonal grains. Small inclusions of gangue minerals are dispersed throughout the sulphides. Pyrrhotite in disseminated or matrix ore may form very irregularly shaped xenoblastic grains with little or no internal strain.

The iron-rich nature of Gellatly ore is indicated in Table 31 and Figure 34.

GORDON SHOOT

Gordon shoot, which has no surface expression, is 300 m east of Gellatly shoot. The opening of a branch from the Gellatly decline to the shoot began in July 1973, but was stopped in September, 40 m from the ore zone, because of bad ground conditions. The pre-mining ore reserve indicates that the shoot is a category 6 deposit.

The shoot which is 300 m long in a north-northwest direction, but only about 30 m wide in plan projection, is on the west-dipping inverted western limb of the Otter syncline. The mineralization occurs 50 to 100 m below the surface in several sheared zones within talc-carbonate-chlorite rocks close to the thick felsic intrusive emplaced on the faulted western limit of the syncline.

LORETO SHOOT

Some nineteen diamond drillhole intersections of contact and hangingwall mineralization are collectively termed Loreto shoot. These occur 1 500 m from Gordon shoot, along strike to the south-southeast. Most intersections are of hangingwall ore present in an area measuring 120 m by 250 m in plan projection. The shoot is within the Otter syncline near its southern termination against outcropping footwall metabasalt.

The bulk of the mineralization is of the hangingwall type present in the inverted western limb of the syncline, where it is known as the Hangingwall A zone (Reeve, 1975a). In diamond drillholes KD 8072A and KD 8213 the mineralization is partly altered (transition zone), and consists of fine- to medium-grained foliated massive ore and breccia ore up to 2 m thick. In one place layered massive ore rests stratigraphically above spinifex-textured serpentine-talc-chlorite + carbonate rock (KD 8213, 34.24 m). Three intersections are in contact mineralization, some 200 m vertically below Hangingwall A, on the basal contact in the uninverted eastern limb of the syncline (Plate 2, section KL). This mineralization is low grade and consists mainly of sulphide veinlets and patches of footwall breccia ore and interpillow sulphide in the footwall metabasalt (Reeve, 1975a). A small zone of mineralization a short distance above this contact is referred to as the Basal Hangingwall zone: it may be offset ore (Reeve, 1975a). The pre-mining ore reserve for the shoot falls into category 6.

ALPHA ISLAND MINERALIZATION (31°14′15″S; 121°41′00″E)

Diamond drilling to the south of Hunt and Lunnon shoots on east-west traverses spaced 200 m apart, has discovered patchy contact and more abundant hangingwall mineralization in the Alpha Island area (Fig. 28). Low-grade contact ore was first discovered west of the island in December 1973 (drillhole KD 3012), but high-grade hangingwall ore was found east of the island in January 1975 (KD 3015). Most intersections of mineralization are east of Alpha Island at depths of 650 to 900 m below the surface of Lake Lefroy. Here drilling on three successive traverses has intersected contact and hangingwall mineralization.

The Kambalda dome plunges south-southeast at about 5 degrees, with moderate dips to the west and steep dips to the east (Arden, 1979). Trough-like structures, free of contact metasediment, are present on both flanks and are generally 70 to 100 m wide and 50 to 70 m deep. The Kambalda ultramafic formation (up to 350 m thick), and particularly the basal member, locally thicken on entering these troughs, where the basal unit normally equates with the basal member of the formation (Arden, 1979). Faults disrupt the troughs, but some do not penetrate right through the overlying ultramafic sequence. The stratigraphy above and outside the troughs is relatively undisturbed (Arden, 1979). Nickel mineralization occurs within and stratigraphically above the troughs, which therefore resemble Lunnon trough, although drilling is insufficient to allow confirmation of whether or not the troughs persist towards Lunnon and Hunt shoots. Several albite-quartz-iron sulphide metasediments occur within the lower part of the ultramafic formation, particularly in the intervening anticlinal crest.

The host olivine peridotite is generally a talc-carbonate rock but some antigorite-bearing rocks occur on the east flank. The footwall metabasalt may be pillowed and biotitic; some more altered chloritic varieties contain networks of quartz-carbonate veinlets (Arden, 1979). Grey dacitic sill-like intrusives, with amphibole or feldspar megacrysts, are common.

The East Alpha Island mineralization constitutes a deposit of category 4 size. Two troughs are present, but mineralization is restricted to a 2 km strike length in the eastern one (Arden, 1979). The widths of mineralized sections are generally less than 1 m. Most mineralization is hangingwall ore present at the base of the second flow unit above the base of the ultramafic formation: pyrite, pentlandite, millerite, magnetite and chalcopyrite occur as disseminations, blebs, veinlets and lenses of matrix to massive sulphides in talc-chlorite-dolomite rocks. Nickel contents of massive sulphides range from 7 to 17 per cent and average 13.7 per cent (Arden, 1979). Pyrrhotite is sparse, which is a contrast with the Lunnon East hangingwall ore to the north. Less than 20 per cent of the mineralization is contact ore present on several disrupted subshoots in the eastern trough. Contact ore is low tenor compared with hangingwall ore: the nickel content of massive sulphide ranges from 4 to 7.6 per cent with a mean of 5.7 per cent. The sulphide mineralogy is pyrrhotite, pentlandite and pyrite (Arden, 1979).

The West Alpha Island mineralization is a category 6 deposit, related to a wide, shallow trough-like structure. Two-thirds of the deposit consists of hangingwall ore associated with well-foliated ultramafic rocks and a sulphidic metasediment at the base of the second flow unit up from the base of the Kambalda ultramafic formation. Pyrrhotite-pentlandite ∓ pyrite assemblages characterize hangingwall and contact ores, but hangingwall ore is of higher nickel tenor with massive sulphide containing 7.4 to 8.9 per cent nickel versus 3.9 to 6.6 per cent for contact massive sulphide (Arden, 1979).

BETA ISLAND MINERALIZATION (31′15′10″S; 121°41′55″E)

High-grade hangingwall mineralization was intersected in September 1977 during diamond drilling (LD 4006) below Beta Island, which is a small island immediately west of the Kambalda - St Ives causeway, 2 km southeast of Alpha Island. South of Alpha Island, the crest of the Kambalda dome tapers, and dips decrease on the eastern flank to about 25 to 30 degrees (Arden, 1979). A large trough-like or synclinical structure immediately east of the crest is referred to as the 'Beta syncline' by Arden (1979), who suggested that this structure may be 400 m wide and 300 m deep (with reference to the ultramafic - footwall metabasalt contact) and result from the merging of the two troughs on the eastern flank at Alpha Island. Narrower troughs occur on both flanks of the dome and in the crest, and are similar in width and depth to those at Alpha Island.

So far only weak mineralization has been encountered in the Beta syncline, although the Kambalda ultramafic formation attains a thickness of 1 500 m or more in the structure. Nearly equal amounts of contact and hangingwall mineralization occur over a strike length of 500 m in a narrow trough developed in the crest of the Kambalda dome (Arden, 1979). This trough may connect with the West Alpha Island trough, both structures being about 130 m wide. However, in contrast with Alpha Island, the contact ore is higher tenor than the hangingwall ore although both consist of pyrite-millerite-pentlandite-magnetite + chalcopyrite opaque mineral assemblages. Arden (1979) reported nickel contents of massive sulphides to be 4.8 to 10.9 per cent (mean 8 per cent), and 3.6 to 24.2 per cent (12.7 per cent) for hangingwall and contact ores respectively.

Beta Island mineralization ranks as a category 5 deposit. It occurs about 500 m below Lake Lefroy.

ST IVES GROUP

GEOLOGY

The St Ives group of deposits is some 20 km to the south-southeast of Kambalda, from where a causeway has been constructed across Lake Lefroy (Fig. 27). As at Kambalda, exploration and development has been entirely carried out by WMC (McDonald, 1976). The deposits occur in the same anticlinal zone of mafic to ultramafic metavolcanic rocks that contains the Kambalda group of deposits. Although the structure is more complex at St Ives, the deposits here are also found on the flanks of plunging anticlines (Fig. 53). The continuation of the axial trace of the Kambalda dome is interpreted by McDonald (1976) as extending across Lake Lefroy (northwest corner of Fig. 53), and forming the major structure (Kambalda - St Ives anticline) in the St Ives region. This interpretation, and that by McDonald of the remaining structure in the region, is dependent upon (a) correlation of all major ultramafic units with the Kambalda ultramafic formation; (b) the use of spinifex textures and trends in magnesia content to establish facing directions; and (c) a distinction between mafic rocks assigned to the footwall metabasalt versus the hangingwall metabasalt formations.

The proposed stratigraphic sequence at St Ives does resemble that at Kambalda (Table 28) and comments will be restricted to important differences. The regional metamorphic grade and style of recrystallization are comparable. The Kambalda ultramafic is thinner (up to 130 m) at St Ives, and the basal olivine-peridotite component of the formation does not exceed 100 m in thickness but it is best developed in mineralized areas. Talc-carbonate alteration is widespread, but antigorite-bearing rocks are present at East Cooee. Sulphidic metasediments are common in the lower parts of the Kambalda ultramafic formation and hangingwall metabasalt formations, and are useful marker horizons in surface geological mapping.

The lower hangingwall metabasalt is thicker at St Ives, being about 250 m thick, and its basal contact with the Kambalda ultramafic formation may be an interfingering one (e.g. Foster area). A conformable unit of metadolerite occurs in the formation in the Foster area. Lenses of uniform peridotitic rocks are present within the lower hangingwall metabasalt to the north and southeast of Jan shoot. The upper hangingwall metabasalt is also thicker at St Ives, and it may grade upwards into more felsic varieites.

Intrusive rocks include felsic porphyries, which are commonest in the north as dykes and sills, weakly porphyritic amphibole-plagioclase-chlorite rocks, and post-tectonic doleritic dykes of probable Proterozoic age. The presence of the mafic intrusives is largely interpreted from detailed aeromagnetic data.

The southeasterly plunging Kambalda - St Ives anticline, east of Foster shoot, exposes a core of footwall metabasalt (Fig. 53). This is faulted down to the north, and is thereby replaced by hangingwall metabasalt, which is in turn in contact with the Kambalda ultramafic formation to the northwest. An inclined anticline, with an axial plane dipping southwestwards occurs to the east of this major anticline, in the Victory area (Fig. 53), but appears to plunge to the southeast. In the East Cooee area the ultramafic rock exposed in the eastern limb of the Kambalda - St Ives anticline is terminated northwards by faults, and reverse faulting also disrupts the footwall metabasalt-ultramafic contact. Deep diamond drilling here has indicated that this contact does not continue to plunge eastwards, but may be involved in a recumbent anticline with a gently southeast-dipping axial surface (McDonald, 1976). This results in ultramafic rock occurring below the footwall metabasalt, though this effect could also be produced by low-angle, east-dipping reverse faulting of the contact zone, a concept which is perhaps enhanced by the presence of a thick felsic intrusive below the metabasalt wedge.

Between East Cooee and Jan shoot is a complex and strongly deformed strip of ultramafic rocks containing several lensoid inliers of footwall metabasalt, which is locally referred to as the 'Jan North attenuation zone' (McDonald, 1976). In the extreme south this zone is represented at Jan Shoot by a nearly isoclinal, inclined anticline whose axial surface dips at 40 to 70 degrees to the southeast. Traced northwards the axial trace of this anticline curves to the north-northwest but the axial surface remains steeply east-dipping. The inliers of the footwall metabasalt may result from boudinage in the core of the fold during north-south attenuation. McDonald (1976) noted that, despite

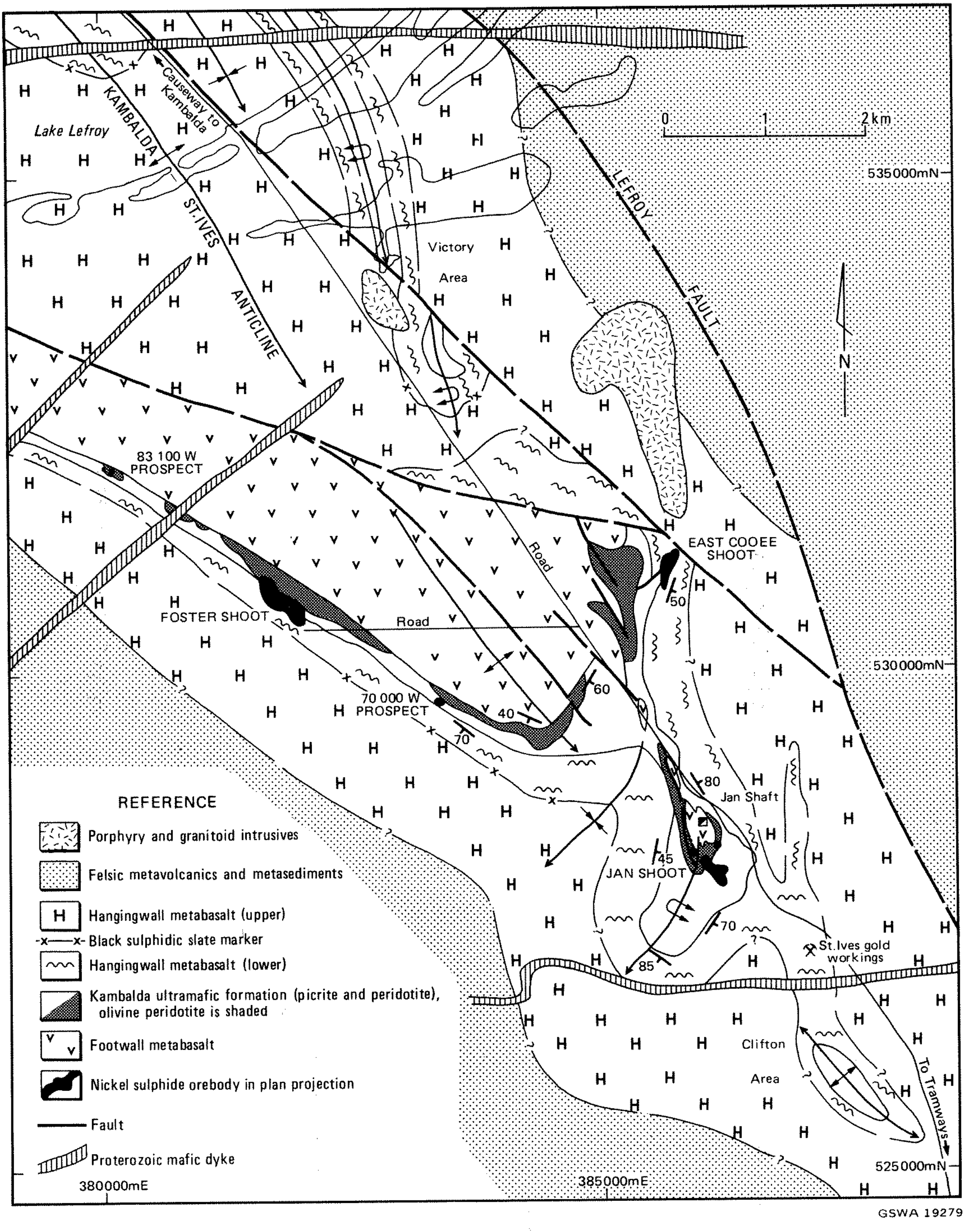

Figure 53. Geological map of the St Ives group of deposits (from McDonald, 1976).

attenuation, the stratigraphy remains more or less complete. He also suggested that the Jan North attenuation zone may have influenced the development of the constricted inclined anticlinal structure in the Victory area.

The tectonic pattern of the whole area is suggestive of interference between an earlier set of northeast-striking folds, some of which are inclined to recumbent(?), and a later set of larger scale, generally upright northwest-striking folds (Fig. 53). This scheme bears comparison with that proposed by Archibald and others (1978) for the Widgiemooltha area to the southwest of St Ives.

Southeasterly plunging structures contain, or are associated with, all the nickel mineralization in the area.

MINERALIZATION

GENERAL

In early 1976 McDonald (1976) estimated that the contained nickel resources in Foster, Jan and East Cooee shoots amounted to 71 per cent of the combined total for the St Ives, Tramways and Republican-Bluebush groups of deposits, and 12 per cent of the total if the Kambalda group is included also. Hangingwall ore accounts for about 60 per cent of the resources of the St Ives group, although recent drilling at Foster shoot has encountered important new contact mineralization. Jan shoot supports the only mine operating in the group.

In Table 30, the ore shoots are graded by the amount of nickel metal in the pre-mining ore reserve, and the arsenic and zinc contents of the ore are also indicated. An association with metasediment characterizes some ore from all three of the shoots. The general character of the mineralization is very similar to that described above for the Kambalda group, particularly the western subgroup.

Gold mineralization is present in the St Ives area, principally at Victory and Orchin mines in the north, and at St Ives itself (Figs 27 and 53). McDonald (1976) stated that the gold is associated with sulphidic metasediments, quartz or porphyry veins that intrude such metasediments, or is on the margins of felsic intrusions emplaced in mafic rocks.

JAN SHOOT (31°22′20″S; 121°47′30″E)

Introduction

Jan shoot occurs at the southern end of the St Ives group. A gossan was discovered in 1966, and subsequent soil sampling outlined a geochemical anomaly. Six gossan samples analyzed by Travis and others (1976) averaged 0.78 per cent nickel, 0.71 per cent copper, 1 061 ppb palladium and 1 572 ppb iridium.

Sinking of Jan shaft began in December 1973 and the first ore production was realized in December 1975. Full production from four levels was achieved in June 1977, and in September 1977 sinking of the shaft was completed at a depth of 618 m below the collar. The mine is now developed on four levels to a depth of 200 m below the surface, with mining being carried out by both slot and cut-and-fill methods using hydraulically placed sand fill and rail-mounted haulage. Current production per four-week period is about 8 000 t of ore averaging 2.5 per cent nickel. Jan shoot ranks as a category 4 deposit in terms of pre-mining ore reserves.

Stratigraphy

The basal high-magnesian part of the Kambalda ultramafic formation is about 150 m thick and consists of thin units of medium- to coarse-grained talc-magnesite + chlorite rock, with subordinate talc-dolomite + chlorite rock, some of which is more chloritic and spinifex-textured in the uppert part of the member (Fig. 54). Talc-chlorite-dolomite rocks overlie the basal part of the formation. Talc or carbonate veinlets are common. Granular carbonate porphyroblasts 2 to 10 mm in diameter are a characteristic feature of the ultramafic rocks and locally the carbonates occur as blebby aggregates. Laminated sulphidic albite-quartz metasediments are well developed in the basal part of the ultramafic formation, but are generally absent from the footwall metabasalt-ultramafic contact irrespective of the presence of contact ore. A persistent metasedimentary horizon occurs about 20 m below the Jan Main subshoot, and metasediment is present at the margins of Jan Main on the 5 level. The metasediments are commonly chloritic at their contacts with ultramafic rocks.

The footwall metabasalt is fine- to medium-grained and is undeformed except for marginal, foliated zones in contact with the ultramafic rocks. An easterly striking altered dolerite dyke bisects the shoot.

General structure

The major part of the shoot is represented by overlapping hangingwall orebodies which form an easterly dipping zone about 100 m wide and at least 350 m long in plan projection (Fig. 54). Dips are in the range 45 to 85 degrees, and average about 60 degrees. The down-dip extent of the shoot remains untested below 350 m below sea level. Metasediment confines at least part of the hangingwall section of the shoot along strike; elsewhere the shoot does not appear to be contained by either metasediments or structural features.

The shoot appears to have a similar plunge to the inclined, tightly appressed anticline which exposes a core of footwall metabasalt immediately to the north (Fig. 54). This structure is further complicated by northerly striking high-angle reverse faults which dip eastwards. Most of the mineralization is within the eastern limb; only contact mineralization has been found in the inverted western limb of the structure.

Ore distribution and structure

Some three-quarters of the mining reserve is contained in two overlapping hangingwall subshoots about 15 m apart which are designated Jan Main and Jan Hangingwall One. Both persist to the deepest levels yet explored, and the Hangingwall One mineralization forms a gossan at the surface. Jan Hangingwall Two and Three subshoots occur at successively higher stratigraphic levels (Fig. 54, cross section), but only Hangingwall Three has sufficient extent to be important as an ore reserve. Contact ore is of more limited extent and irregular distribution compared with hangingwall ore, but it is known from both limbs of the anticline (Fig. 54). Contact mineralization is best developed on the western overturned limb (Jan Western Contact subshoot).

Contact ore consists of lenses of foliated, fine- to medium-grained massive and disseminated sulphides, which are generally not distinctly layered. Massive sulphides are commonly less than 0.5 m thick, and may be present as offset ore. Stratigraphically overlying disseminated sulphides are less than 1 m thick. Disseminated or massive sulphides commonly occur independently of each other. Thickness of the ore section is very variable, and the contacts of ore with wall rocks are generally tectonic surfaces.

Hangingwall ore resembles contact ore in its variable thickness and lensoid distribution, but the overall extent of the subshoots is large. Massive, matrix, disseminated and blebby sulphides are present, but the higher grade sulphides appear to be better developed in the stratigraphically lower subshoots (Jan Main and Jan Hangingwall One).

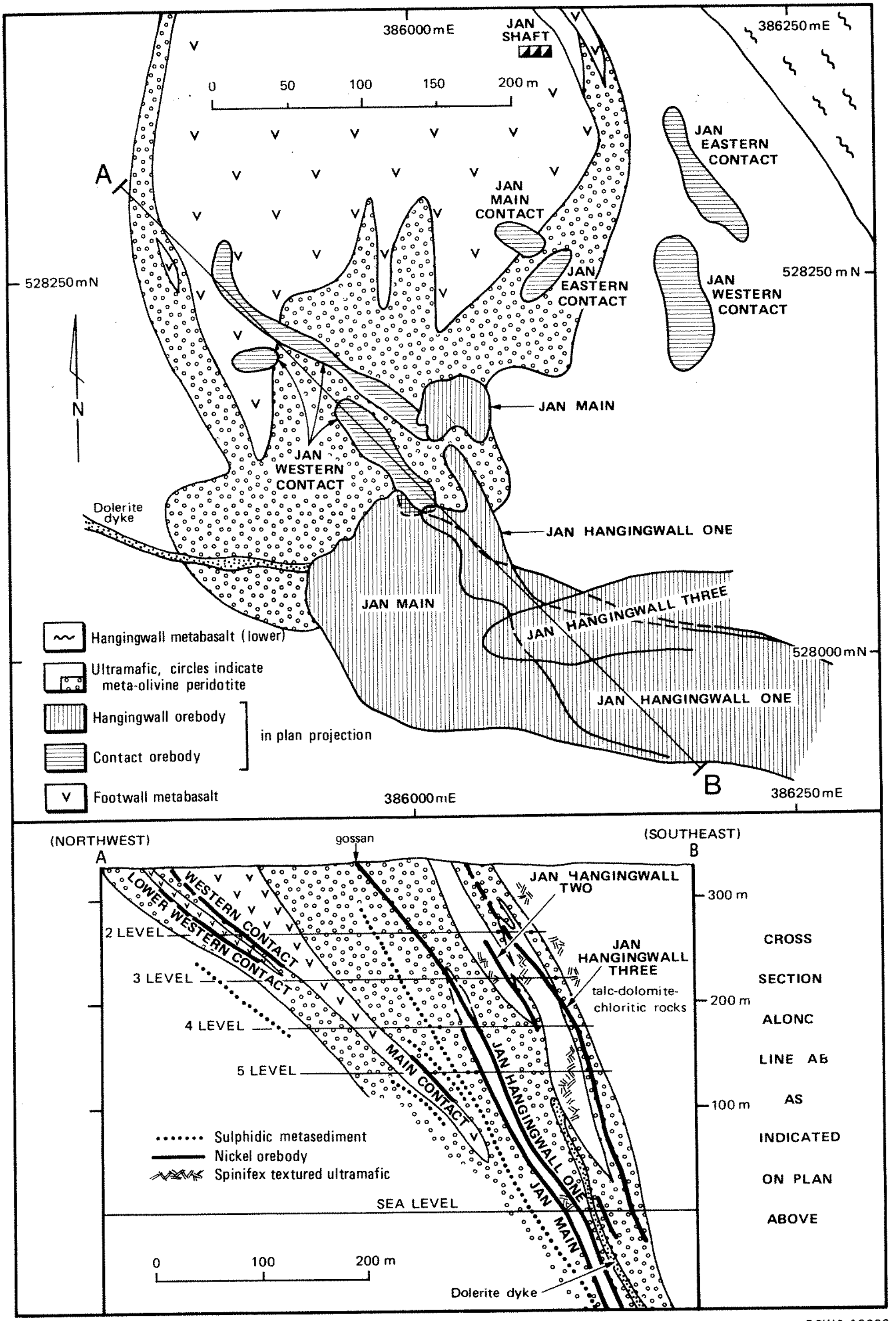

Figure 54. Geological plan and cross section of Jan shoot.

Exceptionally, the ore section reaches 3 to 5 m in thickness, but most massive ore is less than 0.5 m thick and occurs as lensoid masses. Disseminated sulphides are more consistent in distribution and are 1 to 2 m thick. Massive sulphides are fine to medium grained and indistinctly layered.

In many places the ultramafic rocks above and below the ore-bearing surfaces are similar. Spinifex-textured footwall rocks have been observed in Jan Hangingwall Two and Three subshoots in particular, and in rare examples sulphides occur between spinifex plates below weak disseminated ore in granular talc-magnesite (e.g. 504 Cut and Fill North, Jan Hangingwall Three).

Ore petrology

Supergene alteration to violarite-pyrite assemblages occurs to a depth of 180 m, and transitional assemblages extend from 55 m to 270 m depth. At the base of the oxidized zone leached nickel is fixed in the green mineral takovite (Table 11), which is associated with nickel-rich violarite (McDonald, 1976). Primary nickel ore consists of pyrrhotite and pentlandite plus subordinate pyrite, chalcopyrite, magnetite and chromite. Gersdorffite and niccolite occur locally in mineralization in Jan Western Contact, and, where examined above the 4 level, the nickel arsenides form a 2 to 4 cm thick zone marginal to disseminated sulphides. Massive hangingwall ore averages 13 to 16 per cent nickel, whereas much of the disseminated ore averages only 1 to 3 per cent nickel because of its low sulphide content. Massive ore examined contains a fine-scale foliation and a high proportion of gangue (20 to 30 per cent), and could be regarded as fine-grained breccia ore. In general, textural features of the ores appear comparable with those described for the Kambalda group.

Sulphidic cherty metasediment along strike immediately to the southwest of Jan Main ore on 5 level, is itself of ore grade for some 20 m from the edge of normal hangingwall ore. Granular pyrrhotite and pentlandite are accompanied by minor chalcopyrite and rare pyrite, but no chromite is present in the sample examined.

FOSTER SHOOT (31°20′55″S; 121°45′00″E)

Introduction

Foster shoot is 5 km west-northwest of Jan shoot but unlike Jan it has no gossanous surface expression, and terminates about 150 m below ground level. A geochemical anomaly in soil was discovered near the shoot in 1967 and this was tested by drilling, but with negative results. In 1971, deeper diamond drilling designed to test the footwall metabasalt-ultramafic contact intersected the mineralization of Foster shoot. Evaluation of the shoot by diamond drilling continued in 1972, and further drilling took place in 1978 and 1979. The deposit has a size which places it in category 3.

Stratigraphy

The Kambalda ultramafic formation attains a thickness of 150 m, but the upper contact with the hangingwall metabasalt is an interlayered zone rather than a sharp feature (McDonald, 1976). The basal member is some 100 m thick and consists mainly of olivine peridotite, now altered to granular, undeformed talc-magnesite + chlorite rocks with a little antigorite present locally. The metamorphosed olivine peridotites form a thick lens specifically associated with the shoot (Fig. 53). Recent drilling indicates that this lens may thicken downdip of the shoot as it was originally outlined. Several flow units appear to make up the basal member but these have only thin, less magnesian A zones, which may be capped by horizons of sulphidic metasediment.

The footwall metabasalt-ultramafic contact is occupied by sulphidic metasediment for the whole of its subcrop and for distances of up to 400 m down dip. This results in metasediment underlying one-third of the area of contact ore (McDonald, 1976). The footwall metabasalt itself is fine grained, undeformed and locally pillowed. The rock may be foliated and biotitic at the top.

Sills of intermediate rock have intruded the hangingwall metabasalt and the ultramafic rocks, but the southwestern half of the shoot is associated with a sill intruded at or near the base of the ultramafic formation. This sill typically consists of an undeformed biotite- and actinolite-phyric intermediate rock, with marginal chloritic or biotitic metasomatic reaction zones where it is in contact with ultramafic rocks.

General structure

The originally defined dimensions of the shoot in plan projection are 750 m along strike and 50 to 150 m (200 to 300 m down-dip width) normal to the strike. This mineralization occurs in a relatively little disturbed sequence which dips southwest at 45 to 65 degrees. The long axis of the shoot transgresses the strike slightly, and plunges gently to the southeast. However, deeper drilling to the southwest has intersected mineralization in what may be a trough-like structure down dip of the uncomplicated structural environment of the original shoot. An area of barren footwall metabasalt-ultramafic contact appears to be interposed between the two mineralized areas (compare Victor shoot, Plate 2 section EF).

Ore distribution and structure

Most mineralization is contact ore, which lacks any structural control to its limits (in the original shoot), grading into weaker ore then barren zones with or without metasediment present on the contact (McDonald, 1976). Small amounts of low-grade disseminated sulphides occur in several hangingwall positions up to 75 m above the contact. The contact ore occurs above and/or below the sill of the intermediate rock referred to previously, and consists of disseminated sulphides commonly underlain by massive sulphides. The disseminated sulphides may be weakly foliated, and in some places appear to be contained by more chloritic talc-carbonate rocks, some of which are also phlogopitic or tremolitic, that may represent chilled basal zones of ultramafic flows. Massive sulphides are fine to medium grained and foliated, but are not conspicuously layered mineralogically except for lenses of fine-grained pyrite. The contact ore section is normally less than 10 m thick and contains less than 1 m of massive sulphide.

Ore petrology

Supergene violarite-pyrite assemblages are present to 280 m depth, and transition-zone assemblages extend from 165 to 410 m depth. Primary sulphides are pyrrhotite, pentlandite, pyrite and chalcopyrite. Most massive sulphides examined are rich in pyrrhotite and return nickel assays of between 5 and 9 per cent. The mineralization has low contents of arsenic and zinc (Table 30).

EAST COOEE SHOOT (31°20′40″S; 121°47′20″E)

This shoot is an order of magnitude smaller than Jan and Foster shoots. East Cooee shoot is 3 km north of Jan shoot, and was discovered in 1973 during a programme of traverse percussion and diamond drilling. The shoot has no surface expression as the mineralization occurs at depths in excess of 100 m. Demonstrated resources place the deposit in category 6.

The Kambalda ultramafic formation is up to 250 m thick and contains several lensoid olivine-peridotite units, which are up to 50 m thick in its lower part. These units are now represented by granular talc-magnesite + chlorite rocks traversed by talc and carbonate veinlets. The ultramafic rocks dip eastwards at 30 to 60 degrees and overlie footwall metabasalt involved in a recumbent anticline which has a gently southeast-dipping axial surface as described before. Sulphidic metasediment occurs in the footwall metabasalt-ultramafic contact and within the ultramafic rocks and overlying hangingwall metabasaltic sequence. Minor nickel mineralization has been encountered on the lower, inverted footwall metabasalt-ultramafic contact.

East Cooee shoot consists entirely of hangingwall mineralization present in two separate subshoots interpreted as planar and termed Hangingwall Surface No. 1 and Hangingwall Surface No. 2 (McDonald, 1976). Both subshoots are oval in plan projection and occur on flow unit boundaries at the base of talc-magnesite units. Six diamond drillholes intersected Hangingwall No. 1 which measures about 300 m (north-south) by 130 m in plan projection, and occurs 30 to 60 m above the footwall metabasalt-ultramafic contact. Two diamond drillholes 100 m apart intersected Hangingwall No. 2. The mineralized intersections are 0.50 to 7.08 m thick with nickel assays ranging from 1.05 to 8.88 per cent. The higher grade intersections are of less than 1 m. Massive sulphides are correspondingly sparse and thin, the bulk of the mineralization consisting of low-grade disseminated sulphides and blebby sulphides in granular, medium-grained talc-magnesite + chlorite rock.

The mineralization consists entirely of pyrrhotite-pentlandite-pyrite + chalcopyrite assemblages.

83/100 W PROSPECT (31°20′10″S; 121°43′55″E)

Following the discovery of the blind mineralization of Foster shoot, WMC decided on a programme of systematic exploratory drilling of the southwest-dipping ultramafic sequence containing this shoot (Fig. 53). The aim was to test the whole strike length of the ultramafic rocks to a depth of 450 m on a 122 m (400 ft) grid. A few areas with anomalous nickel values were located, but none proved important when followed up with drilling to the 450 m depth limit. The most promising find was 83/100 W prospect near the attenuated northwestern limit of the ultramafic sequence (Fig. 53). However close-spaced follow-up drilling encountered only one sulphide intersection of ore-grade, which returned an assay of 2.61 per cent nickel over 7.74 m (CD 75). This is disseminated, transitional-zone mineralization in talc-chlorite-antigorite + carbonate rock, situated 12 to 20 m above the footwall metabasalt-ultramafic contact. All other ore-grade intersections were in oxidized rock, and McDonald (1976) interpreted the prospect as a small, low-grade sulphide deposit (category 7) which has been enriched in the oxidized zone.

70/000 W PROSPECT (31°21′30″S; 121°46′10″E)

One diamond drillhole (CD 67) intersected 0.5 m of coarse-grained breccia sulphides (assaying up to 3.12 per cent nickel) at the base of medium-grained, cumulus-textured antigorite serpentinite, at this prospect, which is 1.5 km to the southeast of Foster shoot. A siliceous, laminated clastic metasediment occupies the footwall metabasalt-ultramafic contact, and talc-tremolite-chlorite rocks 4 m thick occur between the metasediment and the breccia sulphides.

TRAMWAYS GROUP

GEOLOGY

The Tramways group of deposits is some 40 km to the south-southeast of Kambalda (Fig. 27). Exploration and development in the area has been entirely carried out by WMC (McDonald, 1976). Outcrop is very sparse and geological knowledge is reliant on extensive exploratory drilling and detailed magnetic surveys. The stratigraphy of the Kambalda and St Ives areas is repeated in the Tramways area within a northeast-striking anticlinal zone (Fig. 55). Nickel deposits occur on the southern and eastern flanks of this zone. The regional metamorphic grade and style of recrystallization at Tramways are comparable with St Ives and Kambalda.

The Kambalda ultramafic formation is generally thicker at Tramways compared with St Ives, but variation in thickness (90 m to 480 m) is pronounced. However, olivine-peridotite is less abundant at Tramways, it attains a maximum thickness of only about 40 m, and in most cases is the host rock for nickel mineralization. Talc-carbonate alteration is pervasive. Sulphidic metasediments are common at the basal and top contacts of the formation.

The lower hangingwall metabasalt is up to 350 m thick, which is an increase on the figure for St Ives. The upper hangingwall metabasalt is also thicker at Tramways, and it is overlain by acid to intermediate metavolcanic rocks with interbedded argillaceous metasediments. Acid to intermediate porphyritic intrusive rocks occurring throughout the area are posted-dated by branching doleritic dykes of presumed Proterozoic age.

The general structure is simple, being dominated by two doubly plunging, upright anticlines which have curving axial surfaces oriented northeast (Fig. 55). The anticlines are separated by a complexly faulted, north-striking syncline which opens out to the south but is truncated by a northeasterly oriented fault to the north. This fault, as interpreted by McDonald (1976), truncates the two anticlinal structures and the ultramafic sequence to the north, and appears to have an increasing downthrow to the north as it is traced southwestwards. Another northeasterly oriented fault occurs just north of Edwin and John shoots, but it has little effect on the general structure.

The structure of the northeastern end of the anticlinal zone is complex and bears comparison with the East Cooee area at St Ives (McDonald, 1976). Deep drilling at Cruickshank shoot indicates the presence of a recumbent anticline which plunges to the southeast, and appears to be refolded by the major north-plunging anticline. Faulting repeats the ultramafic sequence to the east of the recumbent anticline.

Dips in the Tramways area are generally in the range of 25 to 45 degrees, with steepening to 60 degrees at the eastern end of the anticlinal zone south of Cruickshank shoot, and to 75 degrees at the western end, west of Edwin shoot. Southeasterly plunging structures contain all the nickel mineralization in the area.

MINERALIZATION

GENERAL

The contained nickel resources of the Tramways group of deposits amount to 22.5 per cent of the combined total for the St Ives, Tramways and Republican-Bluebush groups (McDonald, 1976). Massive sulphides are restricted to Edwin shoot, the only producing deposit in the group. Cruickshank shoot is similar in size to Edwin but contains only disseminated sulphides which occur in a probable metasedimentary rock. The mineralization in both shoots is at the footwall metabasalt-ultramafic contact, and it accounts for nearly 90 per cent of the nickel resources of

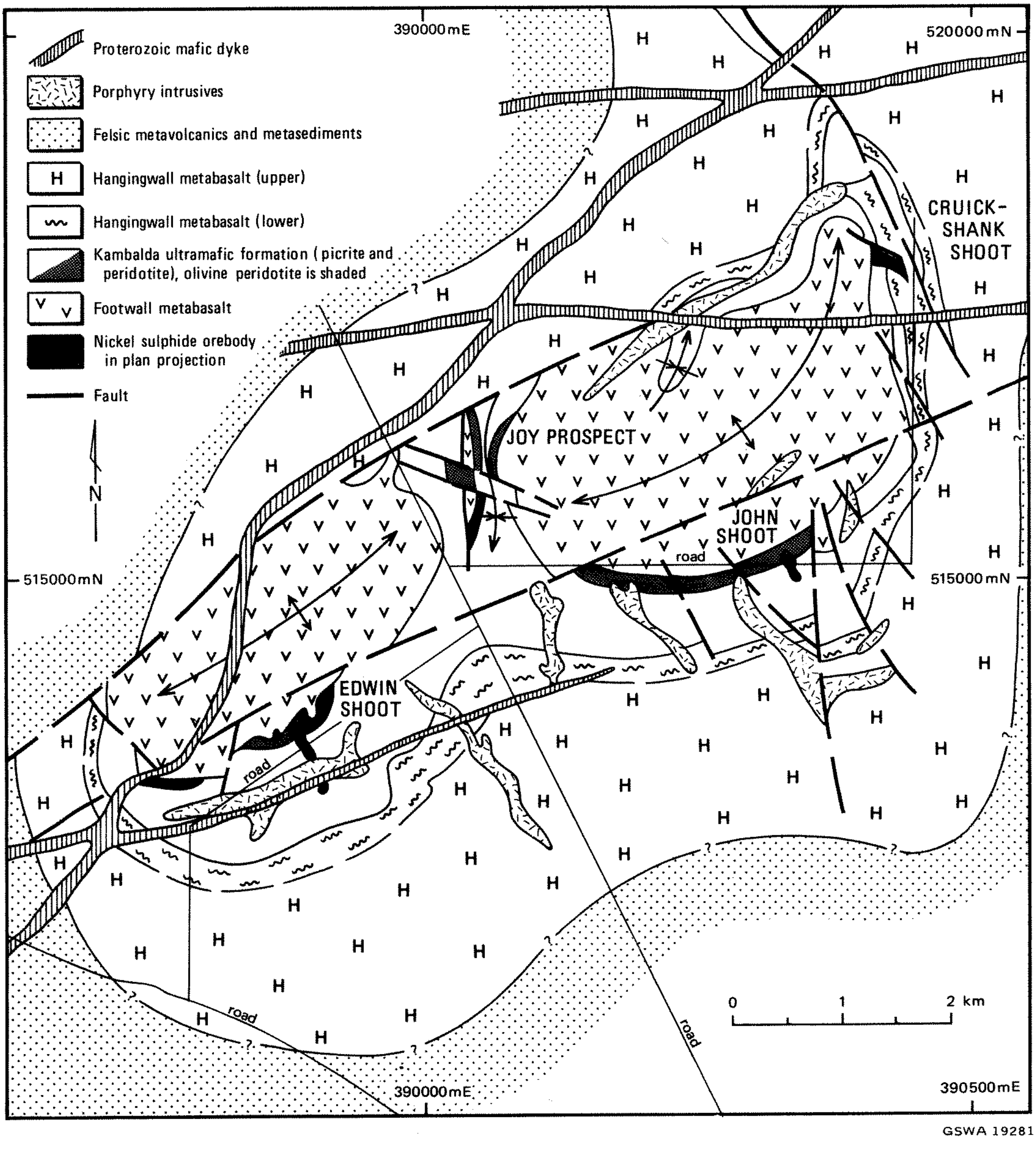

Figure 55. Geological map of the Tramways group of deposits (from McDonald, 1976).

the Tramways group. The remaining mineralization is made up of hangingwall disseminated sulphides in John shoot and Joy prospect. All the deposits, but particularly Cruickshank shoot show an association with sulphidic metasediments which underlie or abut at least part of the nickel mineralization. Confining structures of the type developed at Kambalda are not conspicuous at Tramways.

Cruickshank shoot is described in Chapter 7.

EDWIN SHOOT (31°30′25″S; 121°49′25″E)

Introduction

Edwin shoot is at the southwestern end of the Tramways group. Soil sampling in 1969 revealed a geochemical anomaly in the area, and closer inspection led to the discovery of a small, fragmentary gossan. Percussion drilling in the same year intersected the shoot, and diamond drilling was carried out in the period 1969 to 1971. In 1974 the opening up of an inclined underlay shaft began, and the first ore was produced in December 1975. The mine is developed on three levels to a depth of some 100 m below the surface. Scheduled production is some 25 000 t of ore per year. Edwin shoot is a category 4 deposit in terms of pre-mining ore reserves.

Stratigraphy

The Kambalda ultramafic formation is at its thickest (about 450 m) in the vicinity of Edwin shoot, but the basal unit is only 15 to 35 m thick. In the mineralized area the basal unit is a granular, medium-grained, undeformed talc-magnesite + chlorite rock, which may be capped by a spinifex-textured talc-chlorite-carbonate ∓ amphibole rock between 1 and 2 m thick. A metasedimentary horizon may occur at the top of the basal unit. A less magnesian rock (e.g. talc-chlorite-dolomite, amphibole-chlorite-talc) forms the basal 1 to 2 m of the basal unit in many places, and it may represent a chilled margin.

Sulphidic metasediment is lacking from the footwall metabasalt-ultramafic contact adjacent to the shoot, but thin-bedded quartz-rich metamorphosed sediments or tuffs of intermediate composition occur locally at or near the top of the footwall metabasalt and may underlie contact ore. The footwall metabasalt is fine grained and undeformed, and may contain finely disseminated biotite flakes.

Felsic porphyry intrusions occur in the area, but the most important intrusion is an east-northeasterly striking dolerite dyke which has a sill-like offshoot intruded along the footwall metabasalt-ultramafic contact. This dolerite limits ore-grade mineralization to the south at a depth of 190 m.

General structure

The footwall metabasalt-ultramafic contact in the vicinity of the shoot is deformed by a south-southeast plunging anticlinal flexture. The crest of this flexure is faulted subparallel to the anticlinal axis and contains the shoot which dips at 25 to 30 degrees towards 150 degrees. Including the oxidized zone the shoot is 400 m long (vector 150 degrees) and between 20 and 100 m wide in plan projection. Neither metasediments nor structural features appear to limit the shoot to the east and west. Up dip the shoot extends to within 15 m of the surface where it is displaced from the outcropping gossan by a strike fault. Down dip the main part of the shoot may terminate near the dolerite intrusion, though an important drillhole intersection occurs south of the dolerite.

Ore distribution and structure

The main shoot described above is entirely made up of contact ore, which consists of a thick, central high-grade zone and thin (less than 2.2 m), marginal low-grade zones, which in turn pass laterally into sub-grade and finally barren material. The central zone is widest and thickest in the upper part of the shoot, and comprises massive ore up to 10 m thick (but typically 1 m thick) overlain by sulphide-rich disseminated ore. The low-grade zones contain disseminated ore and little, if any, massive ore. In detail the ore section is foliated and complexly faulted. Most of the ore is in the supergene zone so that many primary ore structures are obscured. However, much massive ore contains inclusions of deformed quartz veins, and the wallrocks may exhibit a mineral lineation parallel to the long axis of the shoot (south-southeast). Lenses and layers of pyrite-rich sulphides within massive ore reflect the presence of originally pyritic sections.

Some 300 m east-northeast of the main shoot is a small area of hangingwall mineralization known as East Edwin Hangingwall. This mineralization consists of thin disseminated sulphides lying 20 m above the footwall metabasalt-ultramafic contact, on a surface which dips east at 18 degrees. The mineralized area is some 150 m long (subparallel to the main shoot) and about 40 m wide in plan projection, and is terminated by a fault to the northeast.

Ore petrology

The supergene zone extends to about 100 m depth which includes all existing underground workings. The assemblage of violarite-pyrite-chalcopyrite + marcasite + millerite (supergene) and rare covellite occurs in this zone. Transition-zone assemblages of pyrrhotite, pentlandite-violarite, pyrite and chalcopyrite are found between 100 and 120 m depth. In the central, high-grade zone of the shoot massive ore averages about 10 per cent nickel and disseminated ore averages between 4 and 6 per cent nickel. The mean Ni:Cu ratio is 15. An isolated intersection in diamond drillhole TD 100, 300 m south of the southern extremity of the main shoot, consists of 10 cm of millerite-pentlandite mineralization.

JOHN SHOOT (31°29′20″S; 121°52′15″E)

John shoot is in a structural position similar to that of Edwin shoot, but is instead on the southeasterly dipping limb of the northern of the two major anticlines (Fig. 55). The shoot was discovered in 1968 by the diamond drilling of a geochemical anomaly outlined by a soil sampling survey. The demonstrated ore resources place the shoot in category 6.

McDonald (1976) estimated the Kambalda ultramafic formation to be 450 m thick. The upper part of the formation is made up of thin picrite to periodotitic flow units. The basal part of the formation is a medium-grained, granular talc-magnesite rock up to 40 m thick, which may have a thin amphibole-chlorite-talc rock at its bottom contact. This contact normally corresponds with the footwall metabasalt-ultramafic contact, but in the upper half of the shoot a laminated sulphidic cherty metasediment occurs in this position or a few metres above the contact (e.g. diamond drillhole TD 56). The footwall metabasalt is fine grained and undeformed, and includes some metadolerite or metagabbro.

The shoot consists entirely of disseminated and blebby sulphides present in a hangingwall position between 1.5 and 10 m above the top of the footwall metabasalt. The sequence dips at 35 to 40 degrees towards the south-southeast. One large and two smaller lenses of mineralization have been defined by five diamond drillhole intersections. The largest lens is 150 m long in the dip direction, 80 m wide normal to this direction, and extends from 40 m to 140 m below the surface. The smaller lenses are to the west, and down dip, of the large lens, at depths of 117 m and 226 m respectively. The ore-section is 2 to

8 m thick and averages 1.0 to 2.0 per cent nickel. Sulphide contents gradually decrease at the margins of the lenses; confining structures to the mineralization do not appear to be present. Pyrrhotite, pentlandite, pyrite and chalcopyrite are the primary sulphide minerals.

JOY PROSPECT (31°29′00″S; 121°50′25″E)

This prospect occurs on the western faulted limb of the syncline separating the two major anticlines of the Tramways region (Fig. 55). Mineralization forms a small surface gossan and dips 40 degrees eastwards to a depth of 70 m where it is terminated by a fault striking northwest. The strike length of the mineralization is a maximum of 80 m. Percussion drilling in 1972 on a 30 m by 30 m grid resulted in five ore-grade intersections but three were in the oxide zone. Disseminated sulphides occur 15 to 20 m above the base of the Kambalda ultramafic formation in a talc-magnesite + chlorite rock. McDonald's (1976) estimate of the demonstrated resources places the deposit in category 7. There appears to be little possibility of increasing the resources.

REPUBLICAN-BLUEBUSH GROUP

GEOLOGY

The Republican-Bluebush group of deposits which is some 50 km south-southeast of Kambalda (Fig. 27), was intensively explored by WMC in the period 1966 to 1976 (McDonald, 1976). Outcrop is generally better than at Tramways, especially in the Republican Hill area.

After consideration of the regional geology, and the detailed mapping reported by McDonald (1976), it is concluded (in agreement with him) that the mafic to ultramafic sequence at Republican-Bluebush is not equivalent to the sequence at Kambalda, St Ives and Tramways. The Republican-Bluebush sequence is regarded as representing a younger episode of mafic to ultramafic volcanism (McDonald, 1976; Williams, 1976). Williams equated the Republican-Bluebush sequence with his Kalpini Group. The sequence can be traced northwards into the Douglas and Yilmia areas (Fig. 27). A generalized stratigraphy is given in Table 34.

The Republican-Bluebush sequence is separated from the Tramways sequence by an unknown thickness of poorly exposed felsic metavolcanic and metasedimentary rocks. Similar rocks overlie the mafic to ultramafic sequence of the Republican-Bluebush area (Fig. 56). The regional metamorphic grade and style of recrystallization at Republican-Bluebush are comparable with Tramways, St Ives and Kambalda, although a somewhat lower metamorphic grade prevails at Republican Hill.

Despite its apparently younger age, the Republican-Bluebush sequence is remarkably similar in internal stratigraphy to the Kambalda – St Ives sequence, consisting of an ultramafic formation which is overlain and underlain by basaltic formations (Tables 27 and 34). Thin horizons of sulphidic metasedimentary rock occur throughout the mafic to ultramafic volcanic succession, which is overlain by felsic volcanic and clastic rock. Nickel mineralization is restricted to the basal part of the ultramafic formation. McDonald (1976) pointed out that the metabasalt below the ultramafic formation at Republican-Bluebush is much thinner than the equivalents at Kambalda and St Ives, and also that komatiitic metabasalt is less abundant in the formation overlying the ultramafic formation at Republican-Bluebush.

TABLE 34. STRATIGRAPHY OF THE REPUBLICAN-BLUEBUSH SEQUENCE

	Lithology	Thickness (m)
5.	Felsic metavolcanic and volcaniclastic rocks	unknown (> 400)
	Laminated cherty sulphidic metasediment	few
4b.	Tholeiitic metabasalt	50-250
	Laminated cherty sulphidic metasediment	
4a.	Komatiitic and tholeiitic metabasalt with proportion of komatiitic rocks increasing downwards	
3b.	Upper ultramafic: thin peridotitic to picritic flow units	150-450
	Cherty metasediment, and metabasalt locally	
3a.	Lower ultramafic: thick peridotitic units and olivine-peridotite lenses, some containing nickel sulphides	
	Laminated cherty sulphidic metasediment	few
2.	Tholeiitic metabasalt and metadolerite	150-300
	Laminated cherty sulphidic metasediment	few
1.	Felsic metavolcanic and volcaniclastic rocks, clastic metasedimentary rocks	unknown (> 400)

Data are from McDonald (1976)

The metabasalts consist of amphibole-chlorite-albite-quartz-clinozoisite assemblages, whereas the metapicrites to peridotites contain amphibole, chlorite, talc and dolomite. The peridotites to olivine-peridotites are mainly represented by talc-magnesite + chlorite rocks, except at Republican Hill where undeformed antigorite serpentinite is well preserved. Flow units of the common cumulate and spinifex-textured types are well developed, those present in the lower ultramafic formation being up to 150 m thick and containing thick B zones. Another type of flow unit seen at Republican Hill consists of (i) zones of bladed to elongate prismatic phenocrysts of antigorite after olivine which alternate with (ii) intervals of closer packed subsequent olivine pseudomorphs accompanied by a smaller proportion of matrix. The olivine phenocrysts may be randomly oriented, or aligned with their long axes in planes which are parallel to the layering in the sequence.

The major structures in the area are the East Bluebush syncline and the adjacent East Bluebush anticline, both of which plunge towards the southeast (Fig. 56). The common limb of these two folds faces west and dips west at 40 to 70 degrees, except at 50 000 S prospect where parasitic folds are present. The attenuation of the mafic to ultramafic sequence northwestwards along this limb is probably caused partly by strike faulting. This sequence reappears in the syncline's western limb which forms the common limb of an anticline to the west (Fig. 27), but nickel mineralization is lacking (West Bluebush area). Intense minor folding and faulting is a feature of the hinge zone of the East Bluebush anticline, and this picked out in outcrop by a metasedimentary horizon at the base of the ultramafic formation. The axis of the anticline plunges moderately to the southeast. The eastern limb of the anticline is complicated by faulting and by folds which are either parallel to the main axis or trend northeastwards (Fig. 56).

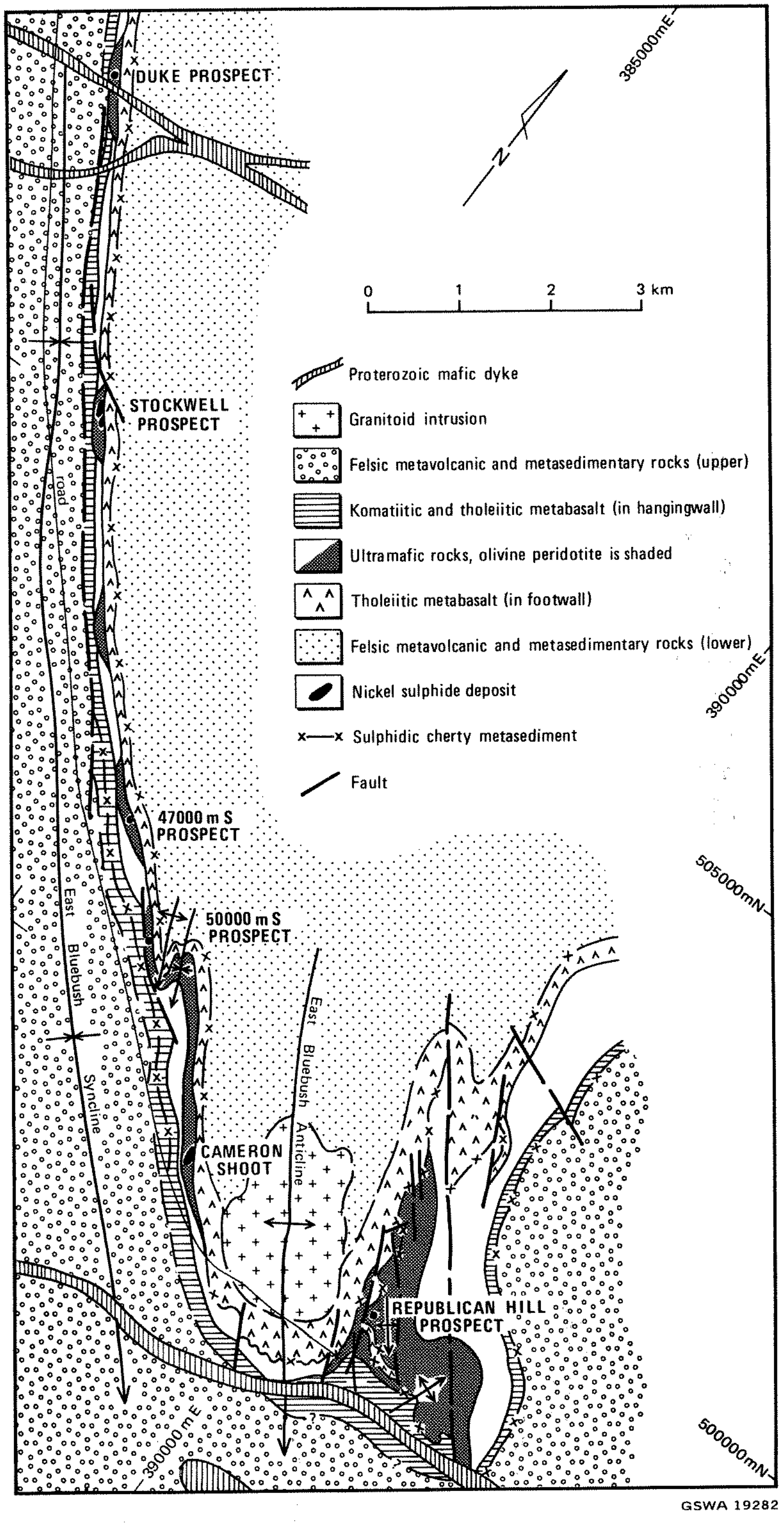

Figure 56. Geological map of the Republican-Bluebush group of deposits (from McDonald, 1976).

McDonald (1976) stated that the steeply northeast-plunging folds are later than the northwest-trending folds, because a steeply dipping cleavage which strikes northwest is deformed by the northeast-plunging folds. There is a real thickening of the mafic to ultramafic sequence in the eastern limb of the anticline but when viewed on a geological map this is exaggerated by the structure.

MINERALIZATION

GENERAL

The contained nickel resources of the Republican-Bluebush group of deposits amount to only 6.5 per cent of the combined total for the St Ives, Tramways and Republican-Bluebush groups (McDonald, 1976). Cameron shoot accounts for 80 per cent of the contained nickel resources of the group. The bulk of the mineralization is at or near the footwall contact of the ultramafic formation and consists of disseminated or blebby sulphides in a weakly foliated talc-magnesite + chlorite rock. Massive sulphides are restricted to thin layers of breccia ore in Stockwell prospect. Most of the deposits are oriented with their long axes parallel to the major folds, but confining structures do not appear to limit the mineralization. None of the deposits has been developed and most remain to be fully evaluated by diamond drilling.

CAMERON SHOOT (31°38′00″S; 121°49′00″E)

The drilling of 29 percussion and 14 diamond drillholes near two gossans was carried out in the period 1972 to 1974. This work was done mainly on a 60 m square grid, and outlined a shoot measuring at least 300 m long (south-southeast) and up to 60 m wide in plan projection. The ultramafic host is a monotonous, granular, medium-grained talc-magnesite + chlorite rock, which contains some antigorite-bearing patches. This rock is rarely foliated, and dips at 60 to 70 degrees towards the southwest. Fine-grained metabasalt and medium-grained metadolerite constitute the footwall to the ultramafic rock, but an albite-quartz + biotite + chlorite + pyrite/pyrrhotite metasedimentary rock is commonly present at the contact. This cherty metasediment may grade up into a chloritic talcose metasediment which is in sharp contact with granular talc-carbonate rocks above.

The mineralization consists of disseminated and blebby sulphides, most of which are irregularly dispersed throughout the basal 40 m of the ultramafic. Most intersections of ore-grade mineralization are only a few metres thick, with nickel contents in the range of 0.5 to 2.0 per cent. The best intersection is 4.82 m assaying 3.29 per cent nickel in diamond drillhole BD 111. McDonald (1976) indicated that the better intersections in the southern half of the shoot have a sill-like metadolerite intrusive immediately below the mineralization. This intrusion and the mineralization appear to be truncated down dip by faulting. The sulphide mineralogy is pyrrhotite, pyrite, pentlandite and rare violarite. The demonstrated resources of the deposit place it in category 5. The shoot remains open along strike to the south.

STOCKWELL PROSPECT (31°34′50″S; 121°45′40″E)

Stockwell prospect is 8.5 km north-northwest of Cameron shoot (Fig. 56). The prospect was discovered in 1975 during percussion drilling of a geochemical anomaly defined by earlier rotary air-blast drilling. Preliminary percussion and diamond drilling on east-west traverses 60 m apart has indicated the presence of three gently south-southeast plunging, elongate lenses of mineralization over a strike length of 850 m. The lenses are arranged in an *en echelon*, non-overlapping pattern, and contain only contact mineralization. Most drilling has been focussed on the central lens which is at least 350 m long (south-southeast) and up to 60 m wide in plan projection.

The ultramafic formation dips southwestward at about 60 degrees. The basal flow unit appears to be up to about 50 m thick in drillholes penetrating the central lens, and is characterized by a spinifex-textured A zone only a few metres thick. The host rock to mineralization in this unit is a medium-grained, granular talc-carbonate + chlorite assemblage, which may be weakly foliated. Deformation is evident throughout the ultramafic formation, and points to the possible attenuation of the mafic-ultramafic sequence by strike faulting, as mentioned earlier. The basal contact of the ultramafic formation with metabasaltic flows and volcanic breccias, and metadolerite is well foliated. Lenses and layers of pyrrhotite or pyrite-rich breccia sulphides up to 15 cm thick occur at this contact. However, disseminated or blebby sulphides in the basal few metres of the ultramafic rock constitute the bulk of the mineralization, but the grade of this mineralization is generally only 1.0 to 1.5 per cent nickel. Pyrrhotite, pentlandite, pyrite and chalcopyrite are the primary sulphides. Some violarite-pyrite supergene mineralization is present. The indicated resources of the prospect rank it as a category 7 deposit.

DUKE PROSPECT (31°33′20″S; 121°44′20″E)

Duke prospect is 3.5 km north-northwest of Stockwell prospect (Fig. 56). The prospect was discovered in 1975 during percussion drilling of a geochemical anomaly defined by earlier rotary air-blast drilling. Eighteen percussion drillholes sunk on east-west traverses 60 m apart have outlined a shoot 200 m long, paralleling the strike, with a width of some 50 m parallel to the dip (50 degrees to the southwest). The shoot appears to be confined laterally by strike faults which have produced a horst-like structure in the metabasalt footwall. Mineralization consists of disseminated and blebby sulphides confined to talc-carbonate-antigorite rocks at the base of the ultramafic formation, apparently only where this overlies the horst-like structure. Shallow drilling down dip of the shoot has only encountered low grade disseminated sulphides in metamorphosed olivine-peridotite. Inferred resources outlined so far place the deposit in category 7.

REPUBLICAN HILL PROSPECT (31°38′10″S; 121°50′45″E)

The Republican Hill prospect is on the eastern limb of the East Bluebush anticline in an area characterized by numerous faults and subsidiary southeast-plunging folds. Gossans in the area were discovered in 1969, but limited percussion and diamond drilling carried out during the period 1969 to 1975 has failed to indicate the presence of important mineralization. Several surface geochemical anomalies in rocks or ironstones appear to be the result of supergene enrichment or weathering of metamosphosed olivine-rich ultramafic rocks. Only three diamond drillhole intersections cut sulphide mineralization which assays more than 0.5 per nickel, the best intersection being 2.62 m averaging 2.4 per cent nickel in drillhole RHD 10. This intersection consists of blebby and disseminated pentlandite and pyrite in serpentinized olivine-peridotite. The host rock contains antigorite pseudomorphs after closely spaced, granular sub-equant olivine, 1 to 3 mm in diameter, or after coarser grained bladed olivine phenocrysts and feathery crystals. The other diamond drillholes cut granular or bladed-textured serpentite with veinlets of pyrrhotite, pyrite, pentlandite plus minor chalcopyrite and rare millerite.

McDonald (1976) commented that some of the percussion drillhole intersections made along strike to the north of the prospect could indicate the result of surface enrichment as interpreted by earlier workers. Inferred resources rank the prospect as a category 7 deposit.

OTHER PROSPECTS

Two small deposits outlined by percussion drilling of gossans or induced polarization anomalies near gossans are known as the 50 000 S (31°37′15″S; 121°48′10″E) and 47 000 S (31°36′45″S; 121°47′30″) prospects respectively. Both occur in basal lenses of talc-magnesite + chlorite rock between Cameron shoot and Stockwell prospect (Fig. 56), and the style of mineralization is comparable with these deposits. The inferred resources of both prospects place each in category 7.

Douglas prospect (31°27′00″S; 121°39′40″E) formerly known as West Peninsula project, is 25 km north-northwest of Cameron shoot (Fig. 27). It is included here because the mafic to ultramafic host sequence is considered to be equivalent to that in the Republican-Bluebush area proper (McDonald, 1976). The prospect occurs in a west-facing and -dipping sequence that is separated by an inferred syncline and strike fault from a comparable sequence to the east. The eastern mafic to ultramafic sequence is a direct extension of that present at Republican-Bluebush. The deposit was found in 1975 during percussion drilling traverses to the south of a geochemical anomaly defined by rotary air-blast drilling. Earlier percussion drilling of this anomaly encountered only weak mineralization in the oxidized zone. Fine-grained pyrrhotite and pentlandite (altered to violarite-pyrite above 50 m depth) are disseminated through a thickness of a few metres in an antigorite-talc-magnesite lens at the base of an ultramafic formation composed of thin picritic to peridotitic flow units. The lens is underlain by black, fine-grained metabasalt. In plan projection the known extent of mineralization measures about 90 m (north-south) by 30 m, and it appears to be mainly fault-bounded (McDonald, 1976). The inferred resources of the prospect rank it as a category 7 deposit.

WIDGIEMOOLTHA GROUP

GEOLOGY

GENERAL

The nickel deposits of the Widgiemooltha group are disposed around a major, doubly plunging anticlinal structure, cored by deformed granitoid rocks, which is known as the Widgiemooltha dome (Figs 27 and 57). The Binneringie dyke forms the southern limit of the group, and a smaller Proterozoic mafic dyke passing just south of Widgiemooltha forms the northern boundary. This northern boundary is arbitrary because the deposits of the Mount Edwards and Spargoville groups form a northward extension of the same mineralized anticlinal zone of mafic to ultramafic metavolcanic rocks (Fig. 27).

Exploration in the region has been carried out by Anaconda and CRA on an equal-interest basis since 1967, although the main period of activity was from 1967 to 1972. In 1972 to 1974 a consortium of Unimin (managers), Laporte and Minimp explored the areas between, and along strike from, the major Anaconda discoveries. Since 1974 exploration has been limited and sporadic. The Redross deposit was mined from 1974 to 1978. Most of the basic geological data relevant to nickel mineralization derive from the efforts of Anaconda and Unimin geologists as reported by Dalgarno (1975), Gemuts and Theron (1975), Eshuys (1975) and Gemuts (1976). More specialized studies include those by Archibald (1980), Joppek (1975), McQueen (1979a), and Willett and others (1978), although N.J. Archibald presents an important re-assessment of the geology of the region based on detailed mapping and structural observations (partly presented in Archibald and others, 1978).

Gemuts and Theron (1975) correlated the mafic to ultramafic metavolcanic sequence at Widgiemooltha with the sequence at Kambalda. The basis for their correlation appears to be as follows:

(a) regional structure, supported by facing evidence derived from lavas and graded bedding;
(b) the presence of nickel deposits in both areas at the base of the first ultramafic sequence below a sulphidic cherty metasedimentary horizon (the so-called 'Black cherty marker');
(c) the presence of granitoid rocks which have intruded the basal part of the sequence in both areas.

The interpreted structure and stratigraphy of the area between Lakes Lefroy and Cowan (McDonald, 1976), which was not part of the study by Gemuts and Theron (1975), lends support to their proposed correlations. This is because metasedimentary, felsic metavolcanic, and mafic to ultramafic metavolcanic rocks, all of which are intrepreted to be younger than the Kambalda - St Ives - Tramways mafic to ultramafic sequence, appear to separate this sequence from the next major anticlinal zone occupied by mafic to ultramafic rocks, which is at Widgiemooltha (Fig. 27). Gemuts and Theron (1975) regarded the mafic to ultramafic sequence at Yilmia as being younger than the Widgiemooltha-Kambalda rocks, and this is substantiated by the northwards strike extension of the Republican-Bluebush sequence. Although the structure is more complex than envisaged by Gemuts and Theron (1975), their broad outline remains valid and represents a major advance in the regional geology. Williams (1976) adopted the same scheme of correlation.

The regional metamorphism is of a higher grade and different style compared with Kambalda. Metamorphic assemblages of middle amphibolite facies prevail and the presence of andalusite and sillimanite in pelitic rocks suggests the pressures were in the range of 200 to 500 MPa (Archibald and others, 1978). Dynamic metamorphic textures are common and may be overprinted by textures indicating static metamorphic recrystallization.

TABLE 35. GENERALIZED STRATIGRAPHY OF THE WIDGIEMOOLTHA AREA

Sequence number	Lithology	Approximate thickness (m)
4 and 5	Felsic metavolcanic and volcaniclastic rocks, and clastic metasediments	unknown (> 500)
	(f) Metabasalt (tholeiitic) with sparsely mineralized ultramafic units mainly near the top; interdigitates with rocks above	250
	(e) Sulphidic cherty metasediment ('Black chert marker')	5-10
3	(d) Ultramafic metavolcanic rocks, basal olivine peridotite unit is commonly *mineralized*	100-600
	(c) Metabasalt, tholeiitic	100-450
	(b) Ultramafic metavolcanic rocks, barren	100-400
	(a) Metabasalt, tholeiitic	

Sequence number from Gemuts and Theon (1975)

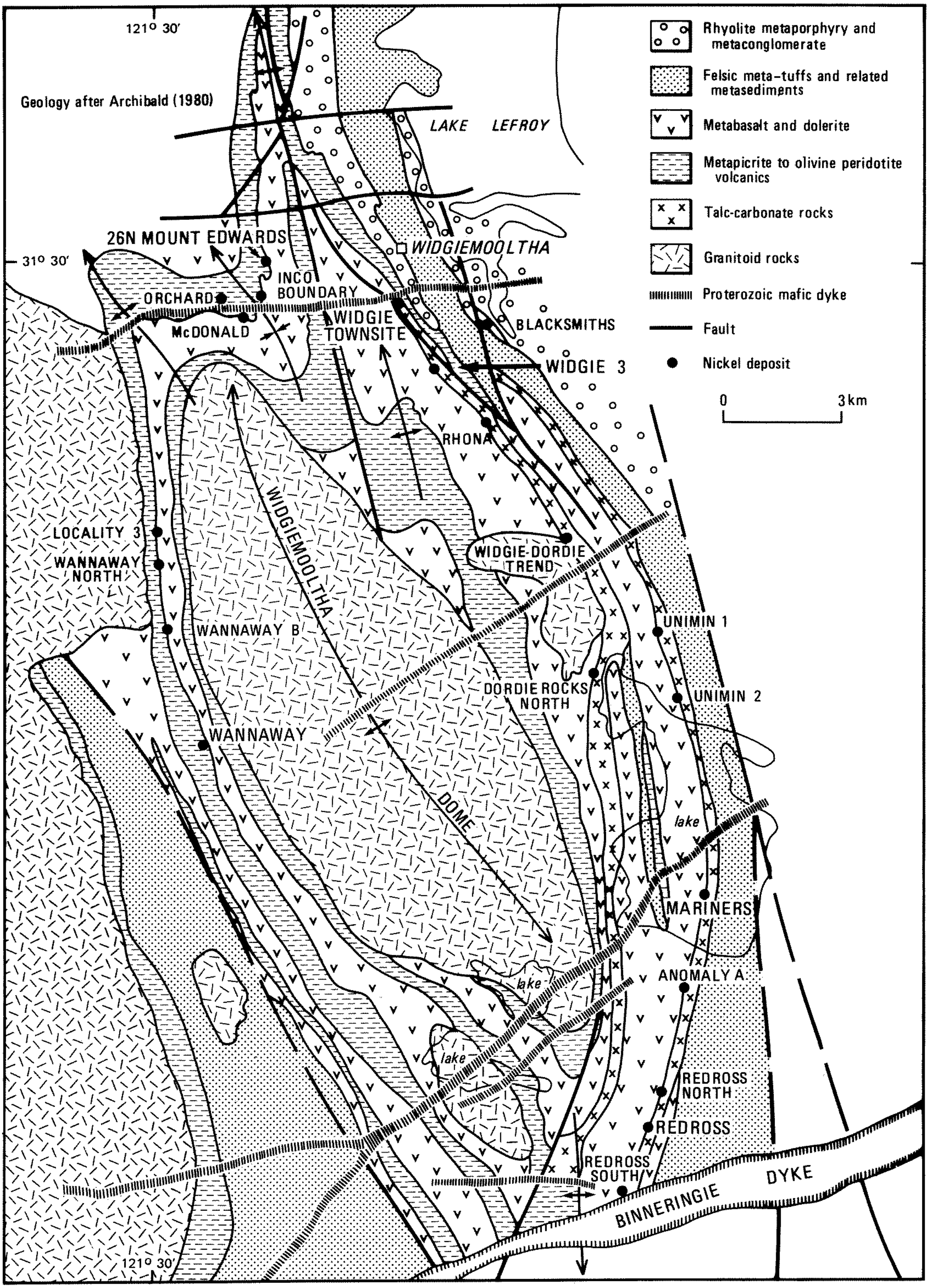

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Figure 57. Geological map of the Widgiemooltha group of deposits. Munda deposit is equivalent to Orchard and McDonald prospects.

STRATIGRAPHY

The general stratigraphy at Widgiemooltha is summarized in Table 35 which is adapted from Gemuts and Theron (1975) and Willett and others (1978). The ultramafic formations of economic interest are labelled (d) and (f) in this table. The apparent thicknesses of formations are variable, partly because of tectonic modification, and the figures given are only an approximate guide. Strike faulting is particularly prevalent along the east flank of the Widgiemooltha dome, and polyphase deformation adds to the difficulty of estimating true stratigraphic thicknesses.

The metabasalts are hornblende-oligoclase/andesine amphibolites which may contain small amounts of quartz, biotite, diopside, cummingtonite, almandine garnet, clinozoisite, sphene, chlorite, prehnite and carbonate minerals. Pillowed, amygdaloidal, and brecciated textures are developed. Limited analytical data suggest that most metabasalt is of tholeiitic affinity.

Common mineral assemblages in ultramafic rocks are as follows (Willett and other, 1978):

(i) tremolite-chlorite ∓ talc ∓ cummingtonite ∓ anthophyllite ∓ olivine ∓ carbonate ∓ plagioclase ∓ biotite

(ii) serpentine ∓ talc ∓ carbonate ∓ tremolite ∓ chlorite

(iii) talc-carbonate ∓ tremolite ∓ anthophyllite ∓ chlorite

(iv) olivine-talc ∓ tremolite ∓ chlorite ∓ carbonate ∓ anthophyllite ∓ enstatite

The olivine (metamorphic), anthophyllite and enstatite in these rocks are commonly retrogressively altered to serpentine (lizardite), talc and chlorite. The rocks of originally olivine-peridotite and dunite composition (Fig. 8) are altered to a great variety of assemblages and textural types. These include granular, cumulus-textured, partly serpentinized olivine peridotite (e.g. Wannaway), a rock with a texture of bladed serpentinized metamorphic olivine overprinted on a foliated talcose matrix (e.g. Munda), and granular to porphyroblastic magnesite-talc + tremolite + anthophyllite rock (e.g. Redross). Talc-carbonate alteration appears to be superimposed on earlier metamorphic assemblages, but carbon dioxide metasomatism appears to have taken place during either prograde or retrograde metamorphism. This alteration is developed only along the east flank of the Widgiemooltha dome, and particularly in the uppermost ultramafic formation (unit (f), Table 35).

In general terms the ultramafic formations resemble the Kambalda ultramafic formation, but they are commonly thinner, most being in the range of 50 to 250 m thick where mineralized. The thicker flow units normally occur towards the base of the formation, but are commonly less than 50 m thick. Basal chill zones rich in tremolite are well developed and contain much of the mineralization.

Thin metasedimentary horizons, mostly of a carbonaceous, cherty sulphidic variety, occur throughout the ultramafic formations, and are present along strike from contact nickel mineralization.

A hangingwall metabasalt formation, comparable in bulk composition and internal stratigraphy to that which overlies the Kambalda ultramafic formation, is not present. The mafic rocks overlying the ultramafic sequence appear to be little different from those which underlie it.

Dyke-like intrusions of quartz-feldspar porphyry, most of which are oriented about parallel with the strike, occur along the east flank of the Widgiemooltha dome. The dome itself consists of granitoid rocks ranging from biotite tonalite to pegmatitic leucogranite, but with an average composition near the biotite granodiorite-adamellite boundary (Archibald and others, 1978), which is distinct from the sodic granitoid at Kambalda.

STRUCTURE

The Widgiemooltha dome, which is the dominant structure, is outlined by a core of poorly exposed, recrystallized granodiorite to adamellite occupying an ovoid area 20 km long and up to 7 km wide (Fig. 57). The granitoid rocks contain a horizontal to sub-horizontal biotite lineation, which, though mainly oriented north-northwest, does appear to radiate outwards from the centre of the intrusion (Archibald and others, 1978). Emplacement is regarded as having been syntectonic and diapiric.

Layering in the mafic to ultramafic rocks dips outwards at between 45 and 85 degrees on the flanks of the dome, but gentler dips of between 20 and 50 degrees characterize the northern and southern extremities of the dome close to the plunging anticlinal axis. A steeply inclined metamorphic foliation is present in many supracrustal rocks and is sub-parallel to the layering. On the flanks of the dome this foliation is parallel to the axial planes of north-northwesterly striking folds, which have been recognized mainly on the eastern flank. This metamorphic foliation is deformed around each extremity of the dome, and strong amphibole lineations in amphibolites plunge parallel to the anticlinal axis of the dome and the biotite lineation in the granitoids (Archibald and others, 1978). To the northeast of Widgiemooltha, Archibald and others (1978) recognized the axial trace of a major early fold which is deformed by the north-northwesterly folds that are congruent with the metamorphic foliation. They also suggested that such early folds may have been responsible for some reversals in the general facing of the mafic to ultramafic sequence. The tectonic history of the area is clearly complex: Archibald and others (1978) recognized four phases of deformation. However, in general, the mafic to ultramafic sequence appears to become younger outwards from the core of the dome.

Nickel deposits are commonly associated with depressions or 'embayments' in the top contact of the metabasalt which underlies the ultramafic formation. Shoots of mineralization plunge parallel to the plunge of these embayments but may also be parallel to (i) local fold axes; (ii) the plunge of faulted wedges of metabasalt; or (iii) the orientation of mineral lineations in the wall rocks (Gemuts and Theron, 1975; Dalgarno, 1975; Barrett and others, 1977). Investigation of the larger deposits shows that the ore shoots plunge at angles varying between 10 and 70 degrees, and have their long axes parallel to the plunge. Deformation during metamorphism was concentrated in narrow zones, particularly along the contact between metabasalt and ultramafic rocks. This has resulted in shoots which are partially offset by reverse faulting into the hangingwall ultramafic rock or the footwall metabasalt (e.g.

Redross, Widgiemooltha 3). However trough-like, fault-bounded, confining structures of the Kambalda type do not seem to be present. Recrystallization outlasted deformation so that faulted or sheared contacts are blurred by static metamorphic textures overprinted on dynamic textures.

MINERALIZATION

GENERAL

About 60 per cent of the identified original resource of nickel mineralization occurs at the base of the second ultramafic formation in the sequence (Table 35 and Fig. 57). The remainder is present in ultramafic units near the top of the mafic to ultramafic sequence. The bulk of the mineralization is concentrated at the basal contact of ultramafic rocks with metabasalt, although tectonic modification has offset some mineralization into the wallrocks. Most deposits are on the east flank of the Widgiemooltha dome, but the largest single remaining deposit is at Wannaway on the west flank.

The style of mineralization is similar to Kambalda, but only two deposits are comparable in size with the moderate-sized shoots at Kambalda. These are the Wannaway and Redross deposits, which each had initial demonstrated plus inferred resources of some 32 000 to and 34 000 t of contained nickel respectively. The Widgiemooltha Townsite (20 000 t contained nickel), Mariners (15 000 t) and Widgiemooltha 3 (13 000 t) deposits are the only deposits of the remainder which exceed a size of 10 000 t of contained nickel. In terms of total nickel resources and the size range of deposits present, the Widgiemooltha group is similar to the St Ives group.

Shaft sinking and the preparation of preliminary surface installations began at Redross and Wannaway in 1970, but the lack of sales contracts led to a suspension of operations the next year. Redross finally commenced ore production in late 1974, but closed at the end of May 1978 after four difficult years in which annual production only once approached the original target figure of 4500 t of contained nickel (Table 2). Investigation of the other deposits has not proceeded beyond the diamond drilling stage. Metals Ex in joint venture with Outokumpu Oy of Finland acquired the rights to the leases over most deposits in the group in April 1979.

The nickel sulphides shoots consist of fine-grained disseminated sulphides and lesser amounts of fine- to coarse-grained massive sulphides, which are typically foliated breccia sulphides containing fragments of deformed metasomatic-reaction-zone rocks, ultramafic host rocks and metabasalt or amphibolite. The massive breccia sulphides are commonly present as lensoid bodies at the base of the ore section, but may also be found as veins transecting disseminated sulphides. Matrix sulphides of the Kambalda type are rare. Mineralogical layering, involving pyrrhotite- and pentlandite-rich alternations and lenses of fine-grained pyrite, is developed in some massive sulphides. Pyrite and/or chalcopyrite may be concentrated at the edges of massive sulphides or in stringers and veins into the wall rocks. Talc-chlorite-tremolite ∓ carbonate rocks are the commonest host to mineralization, the major exception being Wannaway where black serpentinites contain the nickel sulphides.

The nickel content of massive and disseminated sulphides is very variable because of a wide range in Fe:Ni ratios. This is in part probably the result of the complex tectonic history of the region (see also Chapter 2, 'Behaviour during metamorphic processes'). The common primary sulphide minerals are, in decreasing order of abundance, pyrrhotite, pentlandite, pyrite and chalcopyrite. Minor to trace amounts of the nickel arsenides gersdorffite, niccolite and skutterudite, and bravoite and bismuthinite are found in the deposits on the east flank of the dome. Traces of cubanite and heazlewoodite have been reported from deposits on the west flank. Massive sulphides contain up to 20 per cent nickel, but 10 per cent would be a more common figure. Most disseminated sulphides assay in the range between 1 and 6 per cent nickel. The average Ni:Cu ratio for the group is 14, with a standard deviation of 5.

REDROSS DEPOSIT (31°41′10″S; 121°38′50″E)

Introduction

The Redross deposit is at the southern extremity of the group (Fig. 57), some 60 km north of Norseman and a similar distance south of Kambalda. The deposit was discovered in 1968 by D.R. Kennedy who found a gossan which returned an assay of 0.4 per cent nickel and 0.05 per cent copper. Another sample analyzed by Travis and others (1976) contained 0.22 per cent nickel, 0.16 per cent copper, 136 ppb palladium and 465 ppb iridium.

Development of the mine was first begun in September 1970 by the Anaconda (60 per cent) and CRA (40 per cent) partnership, based on a demonstrated plus inferred resource to a depth of 250 m of 984 250 t averaging 3.5 per cent nickel (34 449 t contained nickel) and 0.25 per cent copper. Work ceased in 1971 because of the lack of sales contracts and did not resume until May 1973. Production began in 1974 and to closure on 31 May 1978 the mine produced 13 142 t of nickel in concentrates (Table 2). Remaining demonstrated resources to a vertical depth of 260 m were estimated by Anaconda-CRA (Kavanagh, 1979) to be 703 000 t averaging 2.72 per cent nickel (19 122 t contained nickel), using a cut-off of 1 per cent nickel over 1.5 m true width and including mineralization in crown pillars. Two-thirds of this resource is below the lowest level developed in the mine, which is the 8 level at 90 m above sea level (230 m depth). The shaft has been sunk from the hangingwall side of the deposit to a depth of 256 m (crossing to the footwall side at about 220 m depth), and development has taken place on seven levels. Mining was carried out by cut-and-fill methods using hydraulically placed sand fill, and rail-mounted haulage.

Stratigraphy

The ultramafic formation (part of 3(f) in Table 35) is 60 to 120 m thick and is thoroughly altered to medium-grained talc-carbonate rocks which may contain minor chlorite, anthophyllite and tremolite, particularly towards the base of the formation. Porphyroblasts and veinlets of carbonate minerals occur locally. Nevertheless, sporadically preserved spinifex textures, flow-top structures, and metasedimentary horizons, combined with geochemical variations indicate that the formation is probably at least partly made up of peridotitic lava flows (Barrett and others, 1977, p. 1214). The ultramafic rocks are variably deformed, and may be massive or foliated.

The metabasalt formations present above and below the ultramafic host consist of fine- to medium-grained green-grey amphibolite (green-brown hornblende and plagioclase) which preserves pillowed zones and amygdaloidal textures. A metamorphic foliation overprinted by statically recrystallized hornblende prisms is commonly present.

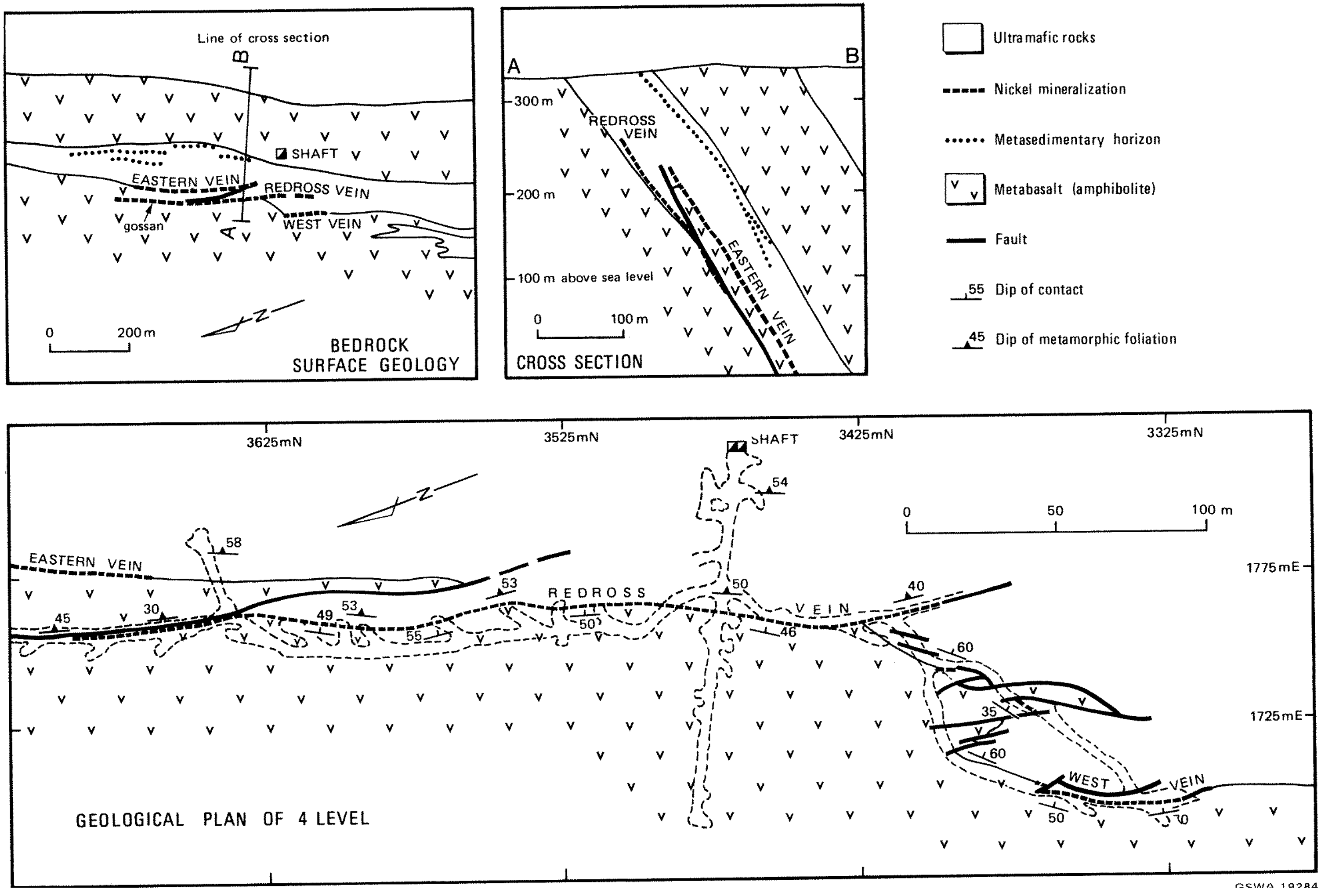

Figure 58. Bedrock surface gology, cross section and geological plan of 4 level, Redross deposit (data from Anaconda Australia Inc).

Metasomatic reaction zones rich in chlorite or biotite are developed along most contacts between metabasalt and ultramafic rocks, including some areas containing contact nickel sulphides. These reaction zones are also found along faulted metabasalt-ultramafic contacts, indicating that much tectonism occurred before or during metamorphism (Barrett and others, 1977).

The metasedimentary horizons are sulphidic and include laminated cherty, carbonaceous and felsic tuffaceous-appearing types. Contacts with ultramafic rocks are commonly rich in tremolite.

General structure

The Redross deposit (Redross and Eastern veins) is largely controlled structurally by the occurrence of a wedge of metabasalt. This wedge has been displaced into the base of the ultramafic formation by reverse faulting subparallel to the layering of the sequence (Fig. 58). Immediately south of the metabasalt wedge is a pronounced westward inflexion or embayment in the metabasalt-ultramafic contact; this structure contains only a small amount of mineralization (West vein). Both structures, and the associated mineralization, dip east-southeast at about 55 degrees and plunge towards the south at about 30 degrees. The strike length of the deposit is 490 m, and its length down plunge is at least 900 m (to 450 m vertical depth). Faulted surfaces confine the deposit marginally in most areas.

Exploration further to the north and south of the deposit has generally not been successful in finding similar structures or mineralization, but encouragement was found marginal to another metabasalt wedge present at depth as a southern continuation of the contact bearing the West vein at higher levels. At a depth of about 260 m (60 m above sea level) this structure has a strike length of about 400 m and a southwards plunge of about 40 degrees (Wolff, 1977).

Ore distribution and structure

Contact and offset nickel ores occur in three shoots which are known as Redross vein, Eastern vein and West vein (Fig. 58). The bulk of the mineralization is in the Redross vein (about 80 per cent) with the remainder mainly being in Eastern vein (about 17 per cent).

In the developed part of the deposit about one-third of the Redross vein is contact ore, the northern third being offset ore in footwall metabasalt, whereas the southern third is offset ore in the ultramafic rock. Below the 7 level (200 m depth) the Redross vein becomes increasingly offset into the footwall metabasalt as the metabasalt wedge extends south to join the northern wall of the embayment. Redross vein is known to extend from the surface to a vertical depth of 450 m, and it remains open below that depth although there is a tendency towards a decreasing strike length with increasing depth.

Disseminated ore, and underlying less persistent breccia ore and massive ore, are up to 5 m thick (but are commonly less than 1 m thick), and typify the contact ore sections in the Redross vein. Ore which is offset into footwall metabasalt in the north is mainly massive sulphide, whereas at the southern end disseminated sulphides with irregular lenses of massive sulphides occur entirely with talc-carbonate rocks. All ore types are foliated, as are the immediate wallrocks. Massive sulphides contain pyrrhotite-pentlandite mineralogical layering and lensoid or rod-like aggregates of fine-grained pyrite. The layering is normally parallel to the margins of massive ore and may be involved in small scale folds which deform the ore section and plunge at about 50 degrees towards the south-southeast (Barrett and others, 1977). Some of the rod-like pyrite has a similar orientation. Deformed fragments up to 0.5 m long of talc-carbonate rock, metasomatic reaction-zone material and metabasalt occur in layered massive ore, and increase in abundance as massive ore grades into breccia ore. Breccia ore is the most important ore type forming extensive thin sheets on the contact and more localized irregular pockets in the footwall (Fig. 59). Lenses of massive or breccia ore may also occur above or within disseminated ore.

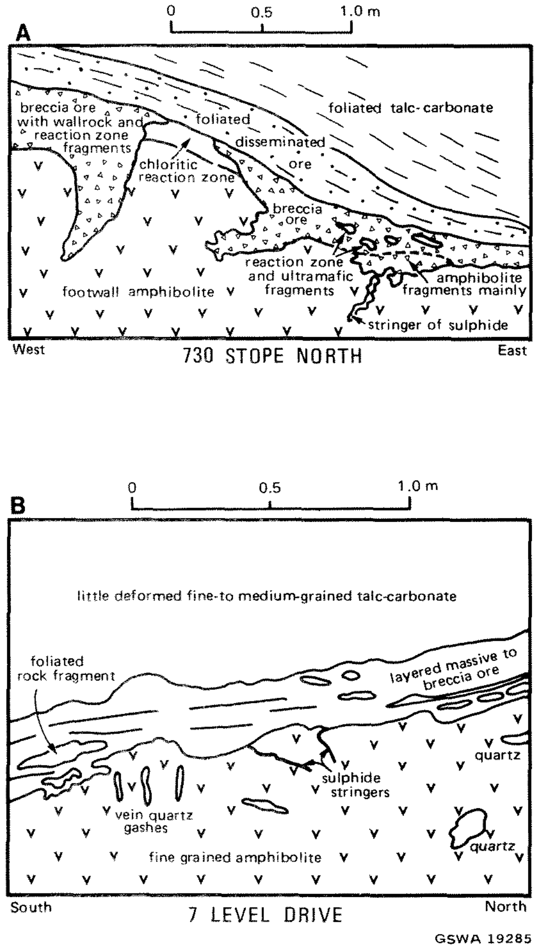

Figure 59. Sketches of vertical underground faces of the central section of Redross vein, Redross deposit.

Eastern vein is shorter in strike length (less than 200 m) and thinner (up to 3 m) compared with Redross vein but it is more consistent in thickness and composition. It consists mainly of disseminated sulphides in the upper levels of the mine. Massive sulphides, generally at the base of disseminated-to-matrix sulphides, occur on the 7 and 8 levels. Deep drilling indicates that Eastern vein breaks up into several smaller lenses of dominantly massive-to-breccia ore below the 7 level. The largest and most persistent of these lenses is known as 'B lens', which is in a position overlying the southern end of Redross vein. At the depth of the projected 11 level (sea level), B lens is about 120 m long, which is about half the length of Redross vein at the same depth.

West vein was not recognized as a separate entity, rather than as an extension of Redross vein, until 1975. However, West vein is very similar to sections of the Redross vein consisting of contact ore, but in general is less than 50 m long and is only present in the upper levels of the mine.

Ore petrology

Primary nickel ore consists of monoclinic pyrrhotite and pentlandite, with lesser quantities of pyrite and chalcopyrite, plus minor chromite and magnetite. A leached, oxidized zone, with siliceous and cellular limonite and rare, small lenses of pyrite, extends from the surface to the water table at 25 to 60 m depth (Dalgarno, 1975). The base of the transition zone is at about 150 m depth. Primary massive ore assays about 9 to 10 per cent nickel, but this may increase to 14 to 17 per cent, particularly where massive sulphide occurs entirely within the amphibolite and is enriched in pentlandite (typically as coarse-grained porphyroblasts to 5 mm diameter). Disseminated ore mainly contains 2 to 6 per cent nickel, with ore from Eastern vein being generally poor in nickel because of a high pyrrhotite:pentlandite ratio. Breccia ore contains amounts of nickel which vary between the nickel contents of disseminated and massive ore. The mean Ni:Cu ratio is 14 but this is highly variable, especially in individual large specimens of massive or breccia ore. Concentrations of chalcopyrite are common in veins and stringers into the footwall, around large rock fragments in breccia ore, and on the edges of massive ore (Barrett and others, 1977).

The mineralogical layering present in massive sulphides is generally on a coarse and laterally impersistent scale; layers are up to 5 cm thick and extend for up to 2 m before pinching out or merging with other layers (Barrett and others, 1977).

Lenses of fine-grained pyrite are conspicuous in some areas. Textures in sulphide minerals are comparable with those described for the Kambalda deposits. Pyrrhotite and chalcopyrite generally lack deformation textures, even though a fine-scale foliation defined by oriented inclusions of gangue and the physical elongation of sulphide minerals is present in massive and breccia ore. In some examples it is evident that large (1 to 2 mm diameter) deformed pyrrhotite crystals have been annealed into mosaics of small, strain-free subequant grains. Elongation of sulphide minerals and aggregates is evident in much disseminated ore, and even that which is apparently not foliated may contain pyrrhotite aggregates which include oriented talc lamellae. The orientation of these lamellae changes abruptly from one pyrrhotite aggregate or large prophyroblast to another.

The mean composition of Redross ore when plotted on an Fe-Ni-S diagram, falls on the sulphur-poor side of the mss field in contrast to most Kambalda ores (Fig. 34). This reflects the generally low pyrite content of Redross ore.

WANNAWAY DEPOSIT (31°36′30″S; 121°31′05″E)

Introduction

The Wannaway deposit is in the centre of the west flank of the Widgiemooltha dome, some 15 km northwest of Redross to which it is linked by a gravel road (Fig. 57). The deposit was discovered by the Anaconda-CRA partnership in 1969 as a result of drilling to investigate geochemically anomalous ironstone samples collected during geological mapping and gossan searching. Small fragments of gossan after massive and disseminated sulphides can be found in and around an old gold prospecting shaft sunk on the amphibolite-ultramafic contact. One sample of gossan after disseminated sulphides analyzed by Travis and others (1976) assayed 0.32 per cent nickel, 0.03 per cent copper, 52 ppb palladium and 15 ppb iridium.

In late 1970 a headframe was installed and a shaft was sunk to a depth of 137 m with a crosscut to the ore zone at about 122 m below surface (4 level). Driving along the ore zone provided bulk samples of metallurgical testing in 1971 and 1972. The shaft remained on a care-and-maintenance basis for a few years afterwards. Anaconda-CRA completed 73 diamond drill holes (total 23 040 m) on 60 m centres and lifts, covering a strike length of about 900 m and to a vertical depth of 365 m. Using a cut-off grade of 1 per cent nickel, Anaconda-CRA (Kavanagh, 1979) estimated a demonstrated resource of 1 348 100 t averaging 2.39 per cent nickel (32 219 t contained nickel) and 0.20 per cent copper. Turner (1976) undertook a re-evaluation of the geology and mineable ore resources of the deposit. For a 3.2 m mining width (includes 1 m total dilution from both walls of the ore zone) he estimated demonstrated resources of sulphide mineralization to 390 m depth (13 level) at 1 384 290 t averaging 2.04 per cent nickel (28 239 t contained nickel), or, if a mining width of 2.2 m was employed, 1 047 228 t averaging 2.65 per cent nickel (27 751 t contained nickel).

In 1980 Metals Ex. drilled six diamond drillholes (total 4 220 m) to investigate the extent of the deposit at greater depth (up to 600 m). More mineralization was discovered, and diluted resources are now estimated at 2.2 Mt averaging 2.2 per cent nickel (1.2 per cent nickel cut-off; 3 m minimum mining width) or 1.4 Mt averaging 3.1 per cent nickel (2.0 per cent nickel cut-off; 2.1 m minimum width).

Stratigraphy

The ultramafic formation (3(d) in Table 35) is 80 to 200 m thick and consists of numerous (at least nine) flow units of picritic to olivine-peridotitic composition, now altered to tremolite-chlorite rock, tremolitic serpentinite, and dark grey serpentinite with some relict forsteritic olivine. Laminated, pyrrhotitic metasedimentary horizons may occur between flows. Some of the flow units are very thin (0.3 to 3.0 m), but the lowest unit appears to be in the range of 20 to 50 m thick with the B zone making up at least 90 per cent of the total unit. The lowest unit is also the most magnesian, containing about 40 per cent magnesia on a volatile-free basis (Groves and Hudson, 1981). A chilled zone some 2 to 3 m thick occurs at the base of the unit and is typified by tremolitic, anthophyllitic or chloritic rocks. Much of the mineralization occurs in this less magnesian, marginal rock type. The ultramafic rocks are generally undeformed and show static igneous textures.

The metabasalt which underlies the ultramafic formation (or rarely underlies a sulphidic metasediment on the contact) is up to 450 m thick and consists of fine- to medium-grained amphibolite which locally contains pillow structures. The presence of green-brown hornblende and calcic plagioclase in the amphibolite, and muscovite-biotite-almandine-andalusite-cordierite assemblages in aluminous metasedimentary rocks, is indicative of regional metamorphism of mid-amphibolite facies (similar to Redross), according to Barrett and others (1977).

Some pegmatite dykes occur in the vicinity of the deposit. A thick sill of metadolerite is present on the western contact of the ultramafic formation (Fig. 60). Metasomatic reaction zones may be developed along amphibolite-ultramafic contacts free of metasedimentary rock.

General structure

The Wannaway deposit is contained in a shallow depression in the amphibolite-ultramafic contact, which dips west-southwest at 60 to 65 degrees (Dalgarno, 1975). At the surface the deposit has a strike length of 370 m, which increases below a vertical depth of 250 m to a length of 460 m. The deposit also plunges northwestwards at 60 degrees and has a plunge length of at least 550 m (Turner, 1976). Cherty, sulphidic metasedimentary rocks present on the amphibolite-ultramafic contact confine the deposit along strike to the north and south. However, the southern limits to mineralization are very irregular and mineralization over a width of up to 1.5 m occurs locally 250 m south of the main deposit. The mineralized stratigraphic section is up to 18 m thick, but commonly is less than about 9 m thick at an average of 1 per cent nickel. Mineralization has been intersected to a vertical depth of 500 m and the deposit remains open at depth.

Ore distribution and structure

Most mineralization in the uppermost 250 m of the deposit is separated from the footwall amphibolite by up to 12 m of barren serpentinite (Dalgarno, 1975) or partly serpentinized olivine peridotite (Fig. 60, cross section). At greater depths the deposit occurs on the amphibolite-ultramafic contact. The bulk of the mineralization (about 90 per cent) consists of fine-grained disseminated sulphides. Massive and breccia sulphides typically occur as thin (about

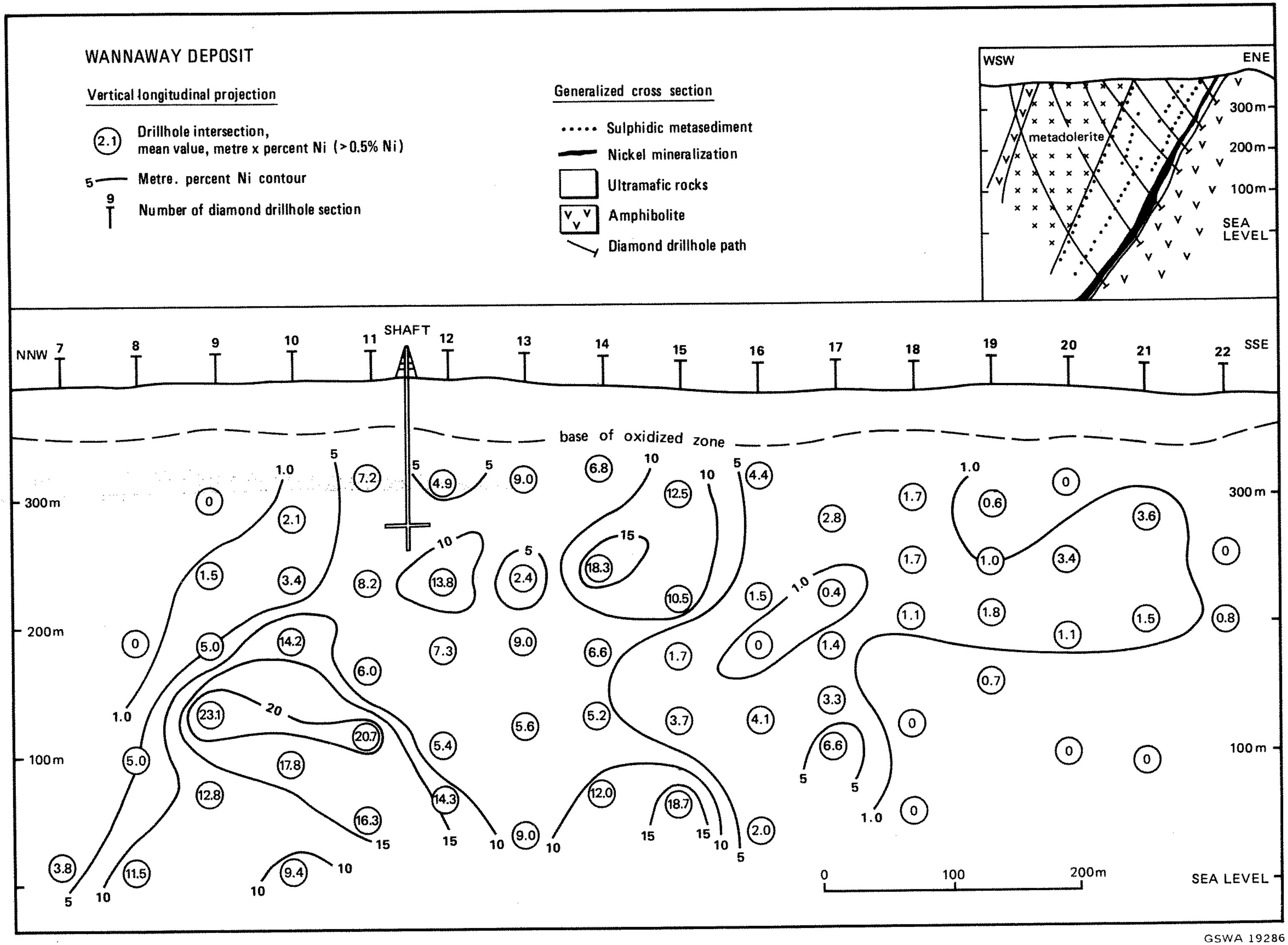

Figure 60. Vertical longitudinal section projection and generalized cross section of the Wannaway deposit. Data on longitudinal projection taken from Turner (1976).

0.3 m) irregular layers and veins in or at the base of disseminated sulphides, and in barren footwall amphibolite or hangingwall ultramafic formation. The sulphide-rich mineralization appears to be controlled by zones of strong foliation and fracturing which can rarely be matched between adjacent drill traverses (Turner, 1976).

The distribution of nickel mineralization in terms of thickness in metres times per cent nickel in drill hole intersections (using a cut off of 0.5 per cent nickel) is shown in Figure 60. The main body of mineralization outlined by the 5 metre per cent contour line increases in strike length from 300 m to 500 m with increasing depth. The high-grade parts of this body are small, the largest one being intersected at a depth of about 250 m on drill sections 9, 10 and 11. Further high-grade parts could exist at depth, for example, around the deepest intersection on drill section 15. Figure 60 also demonstrates the abrupt northern limit to mineralization in contrast to the diffuse southern boundary.

Ore petrology

The primary opaque minerals are pyrrhotite, pentlandite, magnetite, chromite, minor chalcopyrite and rare pyrite and mackinawite. Supergene violarite is present to a depth of at least 150 m in the sulphide-rich ores. The oxidized zone extends to a depth of some 33 m.

Turner (1976) recognized the following five types of sulphide mineralization:

(1) weakly disseminated sulphide — assays up to 1 per cent nickel, rarely recognizable in hand specimen, consisting of very fine-grained pentlandite and minor pyrrhotite;

(2) moderately disseminated sulphide — assays up to 3.5 per cent nickel, consisting of fine- to medium-grained pentlandite and minor pyrrhotite, sulphide content commonly 3 to 8 per cent;

(3) heavily disseminated sulphide — assays between 5 and 12 per cent nickel, consisting of coarse-grained pentlandite in a matrix of silicates, abundant magnetite (up to 30 per cent) and pyrrhotite, generally overlies massive sulphide;

(4) massive sulphide — assays between 1 and 20 per cent nickel, consisting of pyrrhotite, subordinate pentlandite (5 to 38 per cent) and rare pyrite, mineralogical layering may be present;

(5) remobilized sulphide — stringers and irregular streaks of sulphide-rich mineralization in disseminated sulphides.

It is clear from Turner's description of the ore zone (as encountered on the 4 level development drive) and from drill core studies, that much massive sulphide is breccia ore consisting of fragements of amphibolite, chloritic reaction-zone material and serpentinite in a sulphidic matrix. Breccia ore occurs in shear zones or 'veins' and is very irregular in thickness and distribution, resembling the vein-like counterparts at Redross. The drive on the 4 level is 33 m long and exposes breccia ore and heavily disseminated sulphides speckled with abundant magnetite (termed 'leopard ore' by Turner, 1976). The average width of this ore zone in the drive is 1.4 m and the mean nickel content is 4.79 per cent, which reduces to 2.76 per cent nickel for a dilution of 1.2 m during mining (Turner, 1976).

The copper content of the mineralization is up to 0.6 per cent and generally increases in amount downwards (Dalgarno, 1975). Veinlets of chalcopyrite occur in the footwall amphibolite. The mean Ni:Cu ratio is 14 but this increases to 17 in the disseminated mineralization (Turner, 1976). This is the opposite relationship to that commonly seen at Kambalda. The bulk composition of Wannaway ore, when plotted in terms of Fe-Ni-S (Fig. 34), falls near the iron-rich side of the mss field which reflects the pyrrhotite-rich and pyrite-poor nature of the mineralization. The Mount Edwards deposit and Hunt shoot have similar compositions.

The deformed environment in which massive and breccia ores are found is reflected by the sulphide textures. The matrix of pyrrhotite may be schistose, consisting of elongated, sutured grains with films of exsolved pentlandite collected along grain boundaries. Spindle-shaped deformation twins are abundant in pyrrhotite, and several sets, including curving ones, indicate a complex history of strain at elevated temperatures. Cracking and late-stage carbonate veins at right angles to the foliation are seen in some samples. The disseminated sulphides rarely show foliation, but pentlandite is cracked and veined by magnetite, and penetrated by lamellar intergrowths of talc.

WIDGIEMOOLTHA 3 DEPOSIT
(31°31′10″S; 121°35′15″E)

Introduction

The deposit was discovered by R.E. Cotton in February, 1967. A gossanous sample collected from an old gold prospecting pit returned an assay of 1.3 per cent nickel and 0.2 per cent copper. Subsequent geological mapping assisted by the excavation of costeans revealed gossanous material spread along the basal western contact of a serpentinite lens present on the northeastern flank of the Widgiemooltha dome, 3 km south-southeast of Widgiemooltha (Fig. 57). The serpentinite forms a small, prominent hill of massive, buff-weathered rock, which is grey-green where fresh.

Diamond drilling (23 drillholes, total 5 294 m) has tested the deposit to a vertical depth of 300 m. Using a minimum width of 1.5 m at a cut-off of 1 per cent nickel, Anaconda-CRA (Kavanagh, 1979) estimated that demonstrated resources to this depth are 1 080 000 t averaging 1.21 per cent nickel (13 068 t contained nickel) and 0.12 per cent copper. Some mineralization is arsenical. Many drillhole intersections contain about 0.1 per cent arsenic.

Stratigraphy

The ultramafic formation (3(d) in Table 35) here is a maximum of 600 m thick (tectonic complication makes this an apparent figure only), and consists of numerous flow units of picritic to peridotitic composition, now altered to tremolite, chlorite, serpentine, talc and carbonate mineral-bearing assemblages. Lenticular metabasalt or metadolerite units are found in the eastern part of the formation. Carbonaceous or sulphidic, laminated cherty metasedimentary horizons occur between flows, and the margins of these horizons may include layers of coarse-grained, rosetted tremolitic rock. The interlayered nature of the tremolitic rock suggests derivation from a picritic, tuffaceous (?) parent, rather than by metasomatic reaction between siliceous and ultramafic rocks. However, rosetted tremolitic (∓ talc) rocks and biotite- or chlorite-rich material of probably metasomatic origin, are also found along the basal contact zone of the ultramafic formation, and on the contacts between felsic porphyry intrusions and ultramafic rocks.

The grey-green serpentinite which crops out in the hill is variably affected by talc-carbonate alteration, but relict textures of pseudomorphed subequent olivine grains are present (Gemuts, 1976) and indicate a cumulus origin. This olivine-rich ultramafic rock forms an irregular-shaped lens at the base of the ultramafic formation, and is about 110 m long, up to 30 m thick and extends to a depth of at least 300 m below surface. The irregular shape suggests that the olivine-rich ultramafic unit may be an intrusive (subvolcanic?) rather than the B zone of a lava flow.

The footwall rock, to the west of the ultramafic rock, consists of fine- to medium-grained amphibolite, which is only distinctly foliated in the contact zone. The amphibolite may be chloritic and contain coarse-grained prismatic hornblende crystals at the contact with the overlying ultramafic unit.

Dyke-like intrusions of grey quartz-feldspar porphyry have been emplaced approximately parallel to the stratigraphy, and are commonly found adjacent to metasedimentary horizons or the basal contact of the ultramafic unit (Gemuts, 1976).

General structure

The western basal contact of the ultramafic formation dips east at 65 to 80 degrees at the surface, and traces out a pronounced embayment which is partly occupied by the lens of grey-green serpentinite. The embayment is about 130 m long and produces a westwards inflexion of up to 40 m in the contact. At depth, the contact is either vertical or steeply west dipping, and the embayment disappears (Gemuts, 1976).

In plan view the deposit is a gently sigmoidal, lensoid shape some 130 to 250 m long and centred on the northern side of the embayment at the surface. The drilling suggests that the deposit plunges northwards at about 75 degrees. The deposit is up to 19 m thick at its centre and near the top, but it narrows to 3 m or less with increasing depth. The deepest drillhole intersection (WD 19) is 330 m below the surface.

Ore distribution and structure

At the surface two gossans after massive sulphides, up to 20 cm thick, occur on the contact. These gossans are separated by a length of barren north-striking contact containing coarsely rosetted tremolite-talc rocks, and a foliation which strikes oblique to the contact in a north-northwesterly direction. Several vein-like massive sulphide gossans up to 10 cm thick penetrate the footwall amphibolite as offshoots from the basal contact. Drilling indicates that at shallow depth (about 100 m) disseminated sulphides occur between and above the massive sulphide shoots to define the lens-shaped deposit referred to above.

Massive sulphides are generally thin and irregular breccia ore which rarely attains a thickness of 1 m. The breccia ore is fine- to medium-grained and foliated. The breccia ore also occurs in veins in the footwall amphibolite which are parallel to, and are up to 10 m west of, the basal contact. The disseminated sulphides rarely contain more than 10 per cent sulphides and may be weakly foliated.

Ore petrology

The primary opaque minerals are pyrrhotite and pentlandite with minor pyrite, chalcopyrite, magnetite and chromite, and accessory or rare gersdorffite, niccolite, skutterudite and bravoite. The arsenides are commonest in massive sulphides. Minor replacement of pentlandite by violarite has been noted at a depth of 290 m. Violarite is the main nickel mineral from the base of the oxidized zone at 30 m to a depth of about 100 m. Marcasite occurs in the supergene zones. Chalcopyrite is enriched in veinlets marginal to massive sulphides, especially where these enter the footwall amphibolite. The average Ni:Cu ratio is 11, with a range from 3 to 20 (Dalgarno, 1975).

One sample of breccia and disseminated ore showed little evidence of deformation in the sulphide minerals. Static metamorphic intergrowth textures between sulphides and silicates are present.

Massive sulphides are generally rich in pentlandite and return assays of up to 10 per cent nickel, but deleterious amounts of arsenic are present. In contrast, disseminated sulphides rarely contain more than 2 per cent nickel.

WIDGIEMOOLTHA TOWNSITE DEPOSIT (31°30′10″S; 121°34′00″E)

The Townsite deposit (also known as Widgiemooltha 1) is some 2.5 km along strike to the north-northwest of Widgiemooltha 3 deposit (Fig. 57). Following the discovery in 1967 of nickeliferous ironstone material 1 km to the south at David's gossan area on the basal ultramafic contact, Anaconda-CRA extended their exploration northwards to the area of the Townsite deposit, but found little encouragement. A re-assessment by the Unimin consortium in 1973, led to the drilling of 5 diamond drillholes (1 437 m total) to test geochemically anomalous samples from costeans and possible strike extensions of mineralization. The Unimin drilling found low-grade disseminated sulphides and minor massive sulphides in hangingwall zones within the ultramafic formation. Two further diamond drillholes (559 m) sunk by Anaconda-CRA in 1976 and 1977 increased the southward strike extent of this mineralization. Indicated and inferred resources to a vertical depth of 250 m are estimated at 1 Mt averaging 2.0 per cent nickel over a strike length of 550 m (Kavanagh, 1979).

The metavolcanic sequence dips to the east-northeast at 70 to 75 degrees. The ultramafic formation extends along strike from Widgiemooltha 3 deposit, but is truncated at the northern end of the Townsite deposit by a curvilinear fault which is slightly oblique to the strike. Two zones of nickel mineralization have been outlined in the ultramafic formation. The upper zone consists of disseminated pyrrhotite, pentlandite, chalcopyrite and pyrite in a talc-porphyroblastic carbonate + tremolite/anthophyllite + chlorite rock, probably representing the B zone of a lava flow. The lower zone is about 50 m below the upper zone, and consists of similar disseminated sulphides in the basal part of an ultramafic unit underlain by a laminated sulphidic metasediment which is itself nickeliferous. Intervals of layered, fine- to medium-grained pyrite or pyrrhotite-pentlandite + minor gersdorffite massive sulphides up to 0.3 m thick are present in the disseminated sulphides. A further 20 m or so of barren ultramafic rock occurs between the lower zone of mineralization and the basal contact of the ultramafic formation with footwall amphibolite. A barren carbonaceous sulphidic metasediment is present on this contact.

The lower mineralized zone appears to be the most persistent and assays between 1 and 2 per cent nickel over true thicknesses of between 2 and 14 m. In the laminated metasediment the best assay obtained was 5.3 per cent nickel over 0.4 m in diamond drillhole DWT 2 at the northern end of the deposit.

Further drilling is required for an adequate assessment of the deposit and its resources.

MARINERS DEPOSIT (31°37′45″S; 121°39′30″E)

Mariners deposit is located on the southeastern flank of the Widgiemooltha dome, 6.5 km north-northeast of Redross deposit (Fig. 57), and is at a similar stratigraphic level to that deposit (3(f) in Table 35). The deposit is completely concealed by lacustrine sediments. Detailed investigation of linear magnetic anomalies (found earlier by Anaconda-CRA) was begun by the Unimin consortium in 1973. Two magnetic trends were defined using a proton magnetometer. The westernmost of the two trends was drilled first and barren talc-carbonate ultramafic units with intercalated metasediments were encountered. In April 1974, the second diamond drillhole (ME 5) into the eastern magnetic trend intersected nickel sulphides. The indicated and inferred resources to 210 m vertical depth using a 1 per cent nickel cut-off are 1 170 000 t averaging 1.30 per cent nickel (15 120 t nickel) and 0.19 per cent copper (Kavanagh, 1979). Nine of the 21 diamond drillholes (total 4 677 m) intersected mineralized widths assaying more than 0.50 per cent nickel, over a strike length of 750 m. However, the true width and grade of the mineralization averages only 2 m and a little over 1 per cent nickel respectively.

The mafic to ultramafic sequence (Eshuys, 1975) dips eastwards at 40 to 60 degrees. In the vicinity of the deposit there are up to three ultramafic units, 10 to 40 m thick, which are separated by fine- to medium-grained, foliated amphibolite. Overlying the easternmost ultramafic unit is a laminated, sulphidic, carbonaceous metasediment which is 6 to 15 m thick. This metasediment is in turn overlain by medium- to coarse-grained amphibolite which may represent thick flows. The ultramafic units consist of porphyroblastic talc-carbonate, carbonate-chlorite, and tremolite-chlorite-carbonate ∓ talc rocks which are generally foliated, though Eshuys (1975) reported the presence of some relict spinifex and cumulate textures. Basal tremolitic chill zones are present in some units.

Mineralization is mainly restricted to the basal portion of the central ultramafic unit. Low-grade, fine-grained disseminated or coarse blebby sulphides up to 5 m thick overlie irregularly developed layers or lenses of massive sulphides (up to 0.3 m thick) with coarse, lensoid mineralogical layering. Veins of massive sulphides are found in the disseminated sulphides and in the footwall amphibolite where they tend to be rich in chalcopyrite. The primary sulphide mineralogy is pyrrhotite, pentlandite, pyrite, chalcopyrite and accessory gersdorffite. Either pyrite or pyrrhotite may be the dominant iron sulphide. Disseminated sulphide accounts for the bulk of the mineralization, and most contains little more than 1 per cent nickel.

DORDIE ROCKS NORTH DEPOSIT
(31°34′55″S; 121°37′45″E)

This deposit is on the eastern flank of the Widgiemooltha dome, 11 km southeast of Widgiemooltha (Fig. 57), and is at a similar stratigraphic level to the Widgiemooltha 3 deposit (3(d) in Table 35). The terrain is dissected and outcrop is good. In 1967 nickeliferous gossans were discovered by Anaconda-CRA (Gemuts, 1976) at two sites about 350 m apart on the basal ultramafic-amphibolite contact. By mid-1969 the drilling of 23 diamond drillholes (3 660 m total) on lines 61 m apart had outlined two shoots (called A and B, A being in the north). Indicated resources are 190 510 t averaging 2.37 per cent nickel 4 515t contained nickel) and 0.20 per cent copper, calculated to a vertical depth of 275 m using a 1 per cent nickel cut-off and a minimum width of 1.5 m.

The metavolcanic sequence strikes north-northeast and dips eastwards at about 45 degrees. The ultramafic formation is some 300 m thick and consists of picritic to peridotitic flow units which in general become thicker downwards. The basal, mineralized flow is about 20 m thick and is composed mainly of foliated talc + tremolite + chlorite rock with minor carbonate or serpentine, though some less altered serpentinite is present. Thin zones rich in phlogopite and chlorite probably relate to metasomatic reaction zones developed marginally to abundant, steeply east-dipping quartz-feldspar prophyry dykes. These dykes are estimated to occupy some 15 per cent of the ultramafic - footwall amphibolite contact (Gemuts, 1976). The footwall amphibolite is fine to medium grained and is foliated or lineated. Sulphidic metasediment occurs on the contact to the north of A shoot.

The larger of the two shoots is A shoot, which is about 60 m long at the surface, where it occupies an embayment in the ultramafic - footwall amphibolite contact. The shoot plunges gently southwards near the surface but the plunge steepens with depth. The mineralized zone is up to 10 m thick, but is typically 1 to 2 m thick, consisting of low-grade disseminated sulphides with narrow veins of matrix to massive sulphides at or near the basal contact. The southern B shoot is about 60 m long at the surface and has a long axis parallel to the dip direction. This shoot also occupies a depression in the contact, but traced below for about 200 m, and shoots appear to coalesce. The mineralized zone in B shoot is 2 to 4 m thick, but the average grade is lower than that for A shoot.

The primary opaque mineralogy is pyrrhotite and pentlandite with minor chalcopyrite, gersdorffite, magnetite, chromite and bismuthinite. The sulphides show a static metamorphic intergrowth texture with the gangue. The oxidized zone extends to a depth of about 20 m and supergene alteration persists locally to a depth of 250 m or more.

NORTH WANNAWAY DEPOSITS
(31°33′50″S; 121°30′20″E)

This group includes the Wannaway B, Wannaway North (Locality 2) and Locality 3 deposits which are located between 3 and 7 km north-northwest of Wannaway deposit (Fig. 57). The deposits are within the same ultramafic formation present at Wannaway, that here dips westwards at 50 to 75 degrees. Early exploration undertaken by Anaconda-CRA resulted in the discovery of low-grade nickel sulphide mineralization at Wannaway B in a geological setting similar to the Wannaway deposit, 3 km to the south-southeast. The Unimin consortium carried out more exhaustive exploration in the period 1972-1974. The largest deposit was defined at Wannaway North, where an indicated resource of 392 830 t averaging 1.09 per cent nickel (4 282 t nickel metal) and 0.06 per cent copper was estimated, using a 1 per cent nickel cut-off and a 1.5 m minimum width (Eshuys, 1975). Outcrop is restricted to the Wannaway B area where gossans assaying up to 1.18 per cent nickel and 0.17 per cent copper have been found.

The ultramafic formation (3(d) in Table 35) is up to 500 m thick but consists mainly of picritic flows now represented by amphibole-chlorite-serpentine rocks. Thicker, more peridotitic flows with poorly developed A zones occur at the base of the formation, and consist mainly of cumulus-textured serpentinite with minor talc and tremolite. Bladed serpentinized olivines are patchily developed and form a static metamorphic texture overprinted on a static igneous texture. Mineralization occurs in the basal part of the ultramafic formation.

The style of mineralization is similar to Wannaway. Structural features (e.g. embayments) in the footwall amphibolite seem to contain the important mineralization. Low-grade disseminated sulphide predominates. Sulphide-rich mineralization is restricted to local developments of breccia ore on or near the ultramafic - footwall amphibolite contact. The primary sulphide mineralogy is pyrrhotite, pentlandite, pyrite, chalcopyrite and cubanite.

MUNDA DEPOSIT (31°29′55″S; 121°31′20″E)

Munda deposit is located on the northern end of the Widgiemooltha dome, 4 km west of Widgiemooltha (Fig. 57), in the middle ultramafic formation (3(d) in Table 35). The principal deposit coincides with a locality also known as McDonald's gossan. Here diamond drilling, initially by Anaconda-CRA and later by the Unimin consortium (on lines 60 m apart), indicated resources of 245 721 t averaging 1.65 per cent nickel (4 054 t nickel) and 0.10 per cent copper to a vertical depth of 180 m. A 1 per cent nickel cut-off and a minimum width of 1.6 m was used (Kavanagh, 1979). Minor mineralization is present at the Orchard locality, 700 m northwest of McDonald's gossan, and in the 'Inco Boundary area' 1 100 m northeast of McDonald's gossan, where the Anaconda-CRA and INAL-BHP tenements adjoin. Outcrop is fair in the McDonald's gossan area although ultramafic rocks tend to be poorly exposed and oxidized.

The mineralized ultramafic - footwall amphibolite contact dips northwards at 30 to 60 degrees at McDonald's gossan - Orchard, but the strike abruptly changes to north in the Inco boundary area where the dip is at 80 to 85 degrees westwards or eastwards (overturned stratigraphy). This change in strike is caused by the presence of a northwesterly plunging syncline on the northeastern flank of the Widgiemooltha dome. The ultramafic formation is up to 600 m thick and consists mainly of picritic flow units now represented mainly by tremolite-chlorite rocks. These rocks may preserve spinifex textures or exhibit static metamorphic textures; some static igneous textures have olivine porphyroblasts superimposed. Complexly metamorphosed olivine-rich ultramafic rocks occur at the base of the formation and contain serpentinized metamorphic forsteritic olivine, talc, tremolite-actinolite, chlorite, anthophyllite and carbonate minerals in various proportions (Joppek, 1975). The development of a static metamorphic texture of bladed serpentinized olivine superimposed on a dynamic metamorphic texture defined by schistose talc is characteristic. Joppek (1975) regarded the basal mineralized unit as a shallow intrusive and noted that it is 30 m thick in diamond drillhole DDM 8.

At McDonald's gossan the strike length of the deposit is about 360 m and the maximum down-dip length is about 150 m in plan projection. Disseminated sulphides containing 0.5 to 2.0 per cent nickel form the bulk of the mineralization, which is concentrated in the basal few metres of the ultramafic. Pale amphiboles are richer in this section of the ultramafic suggesting that it may represent a chilled zone. Thin zones of layered and foliated, massive to brecciated sulphides assaying up to 16 per cent nickel occur adjacent to the foliated footwall amphibolite and as veins within the amphibolite (Joppek, 1975). The primary sulphide mineralogy is pyrrhotite, pentlandite, chalcopyrite and pyrite, with static metamorphic intergrowth textures developed between sulphides and gangue minerals.

At the Orchard locality, mineralization occurs above the basal contact between two spinifex-textured units. However, the mineralization is restricted to intersections in two drillholes which assayed 3.4 per cent nickel over 1.52 m and 1.01 per cent nickel over 0.9 m (Eshuys, 1975).

At the Inco boundary locality, low-grade disseminated mineralization is present over a thick zone of olivine-rich ultramafic rock some distance above the ultramafic – footwall amphibolite contact. Percussion drillhole HH 520 intersected 3.05 m assaying 1.18 per cent nickel, whereas diamond drillhole DDM 4 140 m to the north intersected 6.37 m assaying 0.64 per cent nickel (Eshuys, 1975). Another diamond drillhole on a traverse 60 m north of DDM 4 failed to find any important mineralization in the same zone.

Additional mineralization could be present down dip of the McDonald's gossan – Orchard area, to the north of an east-trending Proterozoic gabbro dyke.

UNIMIN 1 AND 2 PROSPECTS

These prospects lie on the eastern flank of the Widgiemooltha dome (Fig. 57) in the uppermost ultramafic formation (3(f) in Table 35), situated to the east of the Dordie Rocks North deposit. The bedrock geology is completed concealed by superficial deposits with the exception of some outcrops of amphibolite in the west. The presence of ultramafic rocks was first proved by Anaconda-CRA in late 1968 during a drilling programme which was a follow-up to airborne and ground magnetic surveys along strike from the Redross deposit. The area was termed 'Anomaly B' by Anaconda-CRA and short intervals of disseminated nickeliferous sulphides were encountered at shallow depth in talc-carbonate rocks below 15 m of overburden. Further drilling by the Unimin consortium did not outline mineralization of any importance; Unimin called this prospect 'Unimin 2' (31°34′20″S; 121°39′00″E). The ultramafic formation was traced for some 2 km further north by Unimin and found to be weakly mineralized over a strike length of about 450 m; this prospect was known as 'Unimin 1' (31°34′5″S' 121°38′30″E). Eshuys (1975) estimated indicated resources at Unimin 1 prospect as 92 925 t averaging 1.49 per cent nickel (1 384 t nickel) and 0.16 per cent copper, using a 1 per cent nickel cut-off.

The bedrock geology represents a northward continuation of the easterly dipping sequence at the Mariners deposit, but traced northwards the two ultramafic formations at Mariners appear to merge into one near the northern shore of the salt lake. The single ultramafic formation in the Unimin 1 and 2 areas is overlain and underlain by mafic amphibolite, although laminated sulphidic cherty and carbonaceous metasediment overlies the ultramafic rock in the Unimin 2 area. Medium- to coarse-grained talc-carbonate rocks make up most of the ultramafic formation, with tremolite-chlorite rocks being developed at the top and bottom contacts (Eshuys, 1975). The common distribution of mineralization in drillcore is described as follows by Eshuys (1975):

Top (v) coarse-grained talc-carbonate, 1-2 per cent sulphides
(iv) fine-grained talc-carbonate, up to 5 per cent patchily distributed sulphides 0.3 to 2.7 m thick
(iii) foliated tremolite-talc-chlorite rock, up to 50 per cent, fine-grained sulphides 0.6 to 3.0 m thick
(ii) fine-grained breccia sulphides up to 0.3 m thick
(i) barren, fine-grained amphibolite

The mineralization consists of pyrrhotite, violarite and minor chalcopyrite and is generally iron-rich with an average pyrrhotite:violarite ratio of 5.0. The best intersections at Unimin 1 prospect were in two percussion drillholes on traverse line 3 600 feet north (1 097 m). Drillhole PB 36N-1 intersected a true width of 4.88 m assaying 1.42 per cent nickel, whereas drillhole PB 36N-2 encountered a true width of 3.32 m averaging 2.05 per cent nickel. Two diamond drillholes collared east-northeast of the percussion drillholes, penetrated the ultramafic rocks at depth but did not find mineralization of importance. Drilling along strike to the north and south of this traverse encountered lower grade mineralization. Eshuys (1975) considered that the best mineralization is localized by a fault which cuts across the ultramafic rocks.

The best result obtained during diamond drilling at Unimin 2 prospect was an intersection of 0.76 m (true width) assaying 1.43 per cent nickel and 0.21 per cent copper in drillhole DDB-2 on traverse line 612.5 feet south (187 m) (Eshuys, 1975).

ANOMALY A PROSPECT (31°39′15″S; 121°39′20″E)

Anomaly A prospect is 3 km south of and along strike from the Mariners deposit in an area lacking any outcrop (Fig. 57). The ultramafic rocks were discovered by Anaconda-CRA who drilled 29 short percussion drillholes and undertook diamond drilling on nine traverse lines over a strike length of 1 500 m. The ultramafic formation appears to be a direct strike continuation of the formation containing the Redross deposit.

The drilling by Anaconda-CRA encountred low-grade (up to about 1 per cent nickel) disseminated nickel sulphides and narrow higher grade zones at the base of a coarse-grained, porphyroblastic talc-carbonate. Deeper drilling by the Unimin consortium penetrated the ultramafic to a vertical depth of about 200 m but failed to find any mineralization of note (Eshuys, 1975).

OTHER PROSPECTS

Other prospects remaining to be mentioned fall into two groups. Their locations are shown on Figures 27 and 57. The Davids (31°30′30″S; 121°34′25″E), Rhona (31°31′45″S; 121°35′40″E), Widgie-Dordie Trend (31°33′00″S; 121°37′00″E) and Dordie Rocks South (31°37′00″S; 121°38′05″E) prospects are all within the middle ultramafic formation (3(d) in Table 35) on the eastern flank of the Widgiemooltha dome. The style of mineralization is comparable with other deposits at this stratigraphic level but the amount of mineralization is small, lacks continuity, and generally averages less than 1 per cent nickel.

The Blacksmiths (31°30′20″S; 121°35′40″E), Redross North (31°40′40″S; 121°39′00″E) and Redross South (31°42′15″S; 121°38′30″E) prospects consist of isolated drillhole intersections, generally averaging less than 1 per cent nickel, in talc-carbonate rocks of the upper ultramafic sequence (3(f) in Table 35).

MOUNT EDWARDS GROUP

GEOLOGY

The nickel deposits of the Mount Edwards group occur in the limbs of a complex, north-striking anticlinal structure, known as the Mount Edwards anticline (INAL Staff, 1975).

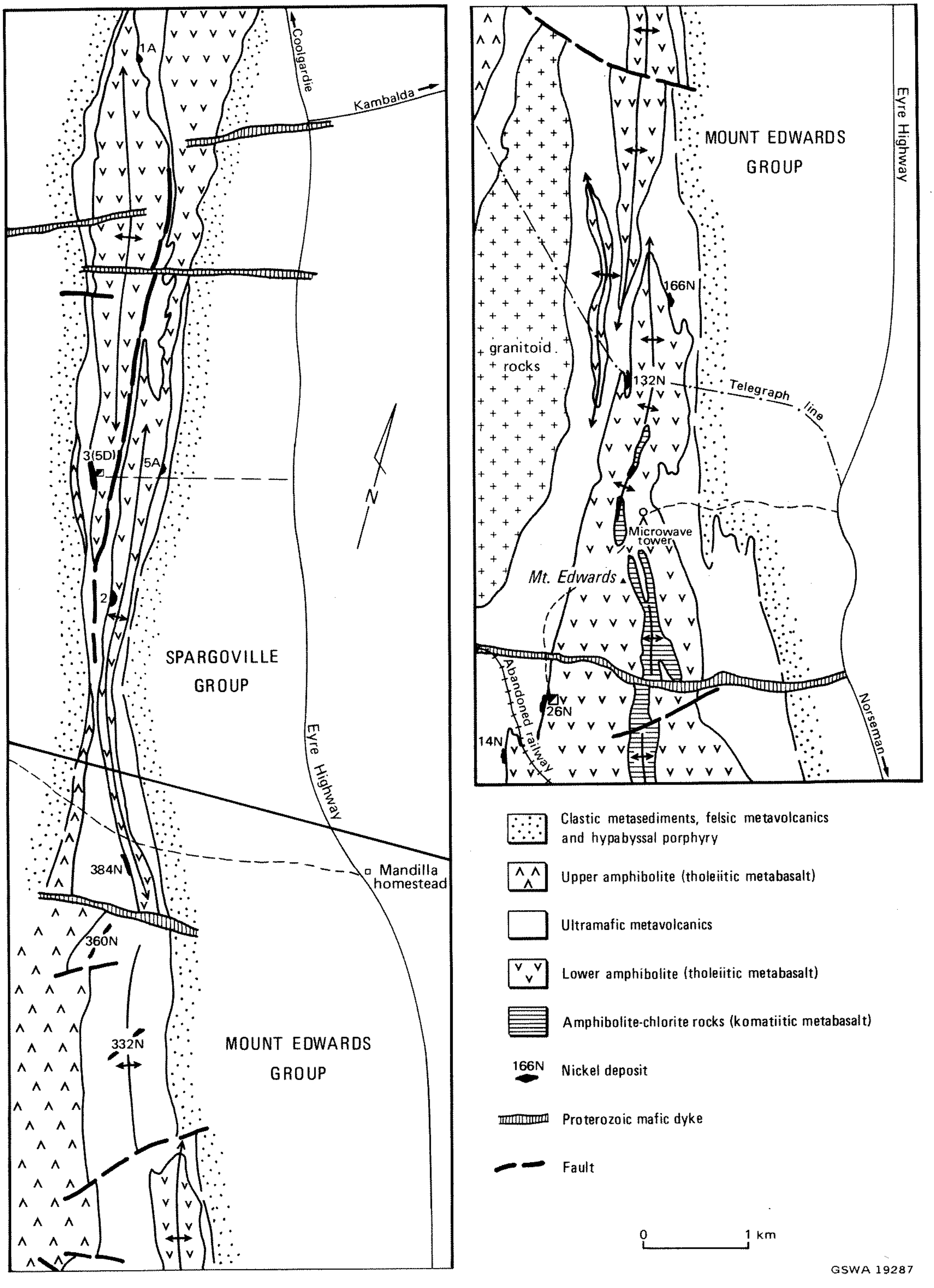

Figure 61. Geological map of the Mount Edwards and Spargoville groups of deposits.

The Mount Edwards group adjoins the Widgiemooltha group to the south and the Spargoville group to the north. All three groups occur in the same mineralized anticlinal zone of mafic to ultramafic metavolcanic rocks (Figs 57 and 61).

A joint venture between INAL (as managers) and BHP has carried out exploration in the area since early 1967, although major activity ceased in 1976. At the largest deposit found, '26N' or simply Mount Edwards deposit, a shaft was sunk and limited underground exploration carried out. The shaft has remained on care and maintenance since it became operational in April, 1972. In November, 1979, it was announced that WMC had taken an option on the mine.

The general stratigraphy of the area (Table 36) is a northwards continuation of that outlined for the Widgiemooltha group (Table 35). The mineralization in the Mount Edwards group appears to be confined to one ultramafic formation which corresponds to the middle ultramafic formation in Sequence 3 of Gemuts and Theron (1975), which is 3(d) in Table 35. The mineralized ultramafic rocks were regarded as part of their 'lower greenstone formation' by INAL Staff (1975), which corresponds with the view of Gemuts and Thorn (1975) that Sequence 3 contains the oldest ultramafic rocks in the region. The felsic rocks at the top of the sequence appear to be in direct contact and infolded with the ultramafic formation along much of the eastern flank of the Mount Edwards anticline.

TABLE 36. GENERALIZED STRATIGRAPHY OF THE MOUNT EDWARDS AREA

Sequence number (equivalent to Table 35)	Lithology
4 and 5	Clastic metasediments, felsic metavolcanic and volcaniclastic rocks with associated hypabyssal porphyry plugs
3f	Metabasalt, tholeiitic
3d	Ultramafic metavolcanic rocks up to 650 m thick, generally more magnesian downwards, punctuated by sulphidic metasedimentary horizons, most nickel mineralization it at or near the basal contact
3c	Metabasalt, pillowed, tholeiitic; subordinate komatiitic types
Granitoid rocks are intrusive into the ultramafics and the upper metabasalt in the west and north.	

Note:
This stratigraphic assemblage is correlated by Williams (1976) with his Mulgabbie Group.

The grade and style of regional metamorphism is as previously described for the Widgiemooltha area. Hough (1976) estimated peak metamorphic conditions as attaining 520 to 600°C at 100 to 300 MPa pressure. The metabasalts are represented by fine- to medium-grained hornblende-plagioclase amphibolites which may be foliated or have a static igneous to metamorphic texture. Limited analytical data suggest that most of this metabasalt is of tholeiitic affinity (Groves and Hudson, 1981). The range of mineral assemblages present in the ultramafic rocks (Table 37) is similar to that described for the Widgiemooltha area, the important difference being a lack of thoroughly metasomatized rocks consisting essentially of talc and carbonate minerals, although such rocks at Widgiemooltha are mainly restricted to the uppermost ultramafic rocks in the sequence. A textural difference is the general lack of relict igneous textures, and the widespread static metamorphic growth of olivine as irregular-shaped to prismatic porphyroblasts in peridotitic rocks. Hough (1976) noted a relationship between the shape of the olivine and the magnesia content of the rock (see Table 37). A characteristic mottled to bladed texture is seen in metamorphosed olivine peridotites which consist of olivine, or retrograde serpentine after olivine, in a matrix of talc plus minor tremolite or chlorite. The fluorine-bearing magnesium silicate clinohumite occurs in some olivine peridotite and may reflect a metasomatic influence from granitoid intrusives. Tourmaline has been recorded from the mineralized sequences in the Widgiemooltha area.

TABLE 37. MINERALOGY AND MAGNESIA CONTENT OF ULTRAMAFIC ROCKS IN THE MOUNT EDWARDS AREA

	Mineralogy	Magnesia content (wt% volatile free)	Rock name: Hough (1976)	Rock name: This bulletin
(1)	Bladed olivine + antigorite + talc + dolomite ∓ chlorite ∓ clinohumite ∓ tremolite	39-45	Low Ca peridotite	Olivine peridotite
(2)	Antigorite	39-45	Low Ca peridotite	Olivine peridotite
(3)	Equant xenoblastic olivine + antigorite + chlorite + tremolite	33-42	High Ca peridotite	Peridotite to olivine peridotite
(4)	Equant xenoblastic olivine + antigorite + talc/anthophyllite ∓ tremolite ∓ carbonate ∓ chlorite	33-42	High Ca peridotite	Peridotite to olivine peridotite
(5)	Porphyroblastic olivine + chlorite + pale actinolite	24-34	High Mg basalt	Picrite to peridotite
(6)	Actinolite + chlorite	20-26	Low Mg basalt	Picrite
(7)	Actinolite + chlorite + calcic plagioclase	15-20	Low Mg basalt	Picrite

Notes:
1. All olivine is of metamorphic origin
2. Data are from Hough (1976)

Despite the lack of primary textures, several features indicate that the ultramafic formation is largely made up of flows. These features are: (i) a regular alternation of mottled to bladed-textured serpentine-talc-tremolite rocks with tremolite + talc + chlorite rocks (cf. Hough, 1976); (ii) the presence of vertical variations in magnesia content comparable with patterns in better preserved ultramafic flow sequences (e.g. Kambalda); and (iii) the presence of thin (1 to 4 m thick) metasedimentary horizons at various levels within the sequence. Drillcore inspection suggests that most flow units range in thickness from 1 or 2 m, to about 50 m, but that in some areas the formation is poorly ordered, there being no clear trend towards an overall downward increase in magnesia content. Hough (1976) reported that the most magnesian flows are up to 100 m thick.

With the exception of underground diamond drillcore obtained during exploratory work from the shaft, all available drillcore is incomplete and consists mainly of small samples considered to be representative of each rock type logged. Outcrop over ultramafic rocks is generally poor to non-existent, and the tremolitic lithologies tend to crop out preferentially. The amphibolites are well-exposed in the south where they form hilly terrain including the Mount Edwards trigonometrical station.

The laminated sulphidic metasedimentary horizons in the ultramafic formation are mainly of a carbonaceous, cherty variety, but chloritic or tremolitic types are also present and may grade into one another.

The north-striking Mount Edwards anticline, the dominant structure, is outlined by the basal ultramafic-amphibolite contact (Fig. 61) although this can only be traced at the surface in the south. The large triangular-shaped area of footwall amphibolite in the south is terminated some 3 km north of Mount Edwards by the steeply north-plunging axis of the anticline. However, a continuation of the anticlinal structure *en echelon* is suggested by a lens-shaped area of footwall amphibolite to the north. Beyond the plunge termination of this area of amphibolite, drilling has revealed that the abnormal width of the ultramafic subcrop is caused by a continuation of the anticline because a core of amphibolite is encountered at a shallow depth. North of the east-striking Proterozoic mafic dyke, amphibolite again appears as subcrop and continues northwards into the Spargoville area. The dip of the layering is generally between 70 degrees and the vertical, and a steeply inclined metamorphic foliation is present in many rocks.

MINERALIZATION

GENERAL

All the mineralization of importance is within 100 m of the base of the ultramafic formation in metamorphosed olivine peridotite flow units, although the chilled basal zones (tremolite-rich) of these units may contain considerable nickel sulphide. INAL Staff (1975) stated that the deposits are associated with embayments in the basal ultramafic-amphibolite contact, although from available information structural irregularities only seem evident at the 26N and 132N deposits. At the 26N deposit, much mineralization is intimately associated with sulphidic metasedimentary horizons. Otherwise, the style of mineralization is similar to that described for the Widgiemooltha group. The size range of the deposits in the Mount Edwards group is also similar. The 26N deposit (33 800 t contained nickel) is comparable in size with Redross or Wannaway deposits, whereas 360N deposit (15 000 t nickel) is similar in size to Mariners deposit. The remaining deposits at 14N, 132N, 166N, 332N and 384N contain between 4 000 and 6 000 t of nickel.

The nickel deposits consist of irregular, multiple lens-shaped concentrations of mainly disseminated sulphides with strike lengths ranging from 200 to 500 m, and with an average thickness of about 5 m. Fine-grained disseminated sulphides form the bulk of the mineralization, but in some bladed-textured ultramafic rocks the sulphides form aggregates which fill, or partly fill the spaces between the olivine (serpentine) blades. This gives rise to a distinctive ore type known as triangular-textured ore, first described from the Nepean deposit by Hudson (1973). Lenses, layers or veinlets of foliated, fine- to medium-grained massive sulphides occur at the base of, or within, disseminated sulphides, but are also found independently in otherwise barren ultramafic or mafic rocks. Most massive sulphide is of the reaction-zone breccia-ore type and contains fragments of ultramafic and metasomatic reaction-zone lithologies, plus amphibolite. Breccia ore at 26N deposit may consist entirely of fragements of metasediment in a massive sulphide matrix. Mineralogical layering is not conspicuous in the samples of massive sulphide examined.

The nickel and copper contents of massive, and to a lesser extent disseminated, sulphides are very variable because of a wide range of Fe:Ni and Ni:Cu ratios. This is probably partly the result of the complex tectonic history of the region. Pyrrhotite, pentlandite and chalcopyrite are the main primary sulphide minerals.

26N (MOUNT EDWARDS) DEPOSIT
(31°29′15″S; 121°32′15″E)

The 26N deposit occurs on the western limb of the Mount Edwards anticline, 3 km west-northwest of Widgiemooltha (Figs 57 and 61). The deposit was discovered in 1967 by the INAL-BHP joint venture. Two samples of gossan after disseminated sulphides assayed by Travis and others (1976) contained 0.1 and 0.2 per cent nickel, 620 and 220 ppm copper, 77 and 30 ppb palladium, and 31 and 9 ppb iridum respectively. A highly siliceous gossan with a coarse boxwork texture crops out for a few metres and probably represents the surface expression of a narrow zone of massive sulphide (INAL Staff, 1975).

A combined exploration/production shaft was sunk to a depth of 280 m in 1969-1971. Exploratory development was done mainly at the 183 m level, and limited underground diamond drilling was undertaken from this level and from depths of 61 m, 122 m and 244 m below the surface. Demonstrated plus inferred resources are 1.7 Mt averaging 2.5 per cent nickel (42 500 t contained nickel) and 0.2 per cent copper, making it a category 4 deposit.

The basal ultramafic-amphibolite contact strikes slightly west of north and is vertical or dips steeply westwards or eastwards. In the vicinity of the deposit this contact is folded and faulted to produce a distinct step visible in plan and cross section (INAL Staff, 1975). The orientation of minor folds in the deposit indicates that the step is a faulted anticline-syncline pair which plunges moderately northwards. However, it also appears that the step partly corresponds to an original depression in the contact, as indicated by the apparent change in thickness of ultramafic rocks below metasedimentary horizons which are thought to be continuous across the step (INAL Staff, 1975).

Nickel mineralization occurs in the basal 100 m of the ultramafic formation, mostly in association with flows of bladed- or mottled-textured metamorphosed olivine peridotite (bulk composition about 40 per cent magnesia) which are less than 60 m thick (Hough, 1976). In several places the presumed flow is only 10 to 20 m thick. The mineralized flow may be the basal one or be up to the fifth one above the basal ultramafic-amphibolite contact (Hough, 1976, Fig. 3.2). A laminated cherty sulphidic metasediment occurs on this contact to the north of the shaft. Elsewhere metasomatic reaction-zone material rich in chlorite and biotite is developed on the contact.

According to INAL Staff (1975) the deposit consists of lenses of dominantly disseminated nickel sulphide, which at the 183 m level are up to 10 m thick and occur over a strike length of 250 m. As exposed on the 183 m level the dominant ore type is low-grade (5 to 10 per cent sulphides), fine-grained disseminated sulphide in bladed- or mottled-textured serpentine-talc + tremolite rock. Small patches (less than 0.5 m thick) of more sulphide-rich disseminated ore, triangular-textured ore (Fig. 92A) and foliated, fine- to medium-grained massive ore, are found close to the contact, in association with more tremolitic rocks in some cases. Irregular veins of massive ore also penetrate the footwall amphibolite. Breccia ore seems particularly well developed where massive sulphides are in contact with the sulphidic metasedimentary horizons. The fragments in the sulphides are of metasediment in various states of disruption. Pyrrhotite, pentlandite and chalcopyrite are the chief primary sulphides. Pyrite and cubanite may be present in small amounts.

Massive and breccia ore examined lacks distinct mineralogical layering, but contains a fine-scale foliation defined by oriented gangue inclusions and elongated pyrrhotite. The pyrrhotite commonly contains abundant deformation twins and kink bands oriented at various angles to the foliation. Annealed textures are poorly developed. Breccia ores tend to be richer in pyrrhotite, and some contain coarse-grained pentlandite up to 10 mm in diameter. The disseminated and triangular-textured sulphides are generally little deformed and show recrystallization between silicates and sulphides.

Massive sulphides contain between 8 and 16 per cent nickel, though some breccia ores are pyrrhotite-rich and may contain only a few per cent nickel. Disseminated sulphides contain less than 3 per cent nickel and grade into sub-grade material containing less than 1 per cent nickel. Naldrett and others (1979) gave the following mean metal contents for six samples of ore, with values recalculated to 100 per cent sulphide: 11.30 per cent nickel, 1.31 per cent copper, 0.27 per cent cobalt, 421 ppb platinum, 1 063 ppb palladium, 121 ppb iridium and 67 ppb gold.

360N DEPOSIT (31°24′05″S; 121°31′05″E)

This deposit is 9 km north-northwest of Mount Edwards (Fig. 61), in a soil-covered area. Demonstrated and inferred resources make it a category 4 deposit (Fig. 16). The ultramafic formation resembles that at 26N deposit, though it may be less magnesian overall. In diamond drillhole Z8137A, mottled to bladed-textured rocks consisting of partly serpentinized olivine with talc and tremolite, alternate with fine- to medium-grained rocks rich in tremolite. However, the basal 38 m of the ultramafic formation in this drillhole consists exclusively of variably foliated, fine-grained tremolite + chlorite rocks which are devoid of mineralization. The mineralized zone is 10 m above the top of these tremolitic rocks, and lies at the base of a coarsely mottled olivine-talc-tremolite unit which is about 13 m thick. In drillhole Z8137A the mineralized zone is 8 m thick overall (including sub-grade sections assaying less than 1 per cent nickel), and is mainly composed of fine-grained, unfoliated disseminated sulphides in mottled to bladed-textured ultramafic and tremolitic ultramafic rock. Small patches of triangular-textured ore are present. Medium-grained, foliated pyrrhotite- and pentlandite-bearing breccia ore forms a sharply bounded layer 0.5 m thick in the centre of the disseminated mineralization. This layer contains about 15 per cent nickel. The disseminated sulphides contain up to about 4 per cent nickel and consist of pyrrhotite and lesser pentlandite intergrown with rosetted amphibole and granular olivine. The pyrrhotite is very fine grained and forms well-annealed aggregates of polygonal grains which lack any distinct foliation.

332N DEPOSIT (31°24′30″S; 121°31′15″E)

The 332N deposit is located 1 km southeast of 360N deposit in an area of poor outcrop which straddles the anticlinal axis continuing north from Mount Edwards (Fig. 61). The deposit contains demonstrated plus inferred resources which make it a category 5 deposit. In plan projection the deposit is lens-shaped and is elongated in a northeasterly direction. Mineralization occurs at the basal contact of the ultramafic formation, which dips west at about 45 degrees or east at about 60 degrees in the vicinity of the deposit. The footwall amphibolite forming the core of this anticline is encountered at a shallow depth in diamond drillholes. The petrology of the ultramafic formation is similar to that described for 360N prospect. Medium-grained, massive granitoid rocks have intruded the upper part of the formation in the west in both areas.

In diamond drillhole Z8149 the mineralized zone is about 3 m thick and occurs at the base of a mottled to bladed-textured olivine/serpentine-tremolite/anthophyllite + talc + chlorite rock unit. Fine-grained disseminated ore containing up to 30 per cent sulphides, makes up the bulk of the mineralization, and has a static metamorphic intergrowth texture with silicates (e.g. amphibole rosettes). Triangular-textured ore is patchily developed near the top, and fine- to medium-grained pyrrhotite + pentlandite breccia ore forms a 12 cm thick layer at the base of the ore section. In a sample of disseminated sulphide examined, pyrrhotite is the dominant mineral occurring as very fine polygonal grains showing little internal strain, presumably because of annealing. Pentlandite is coarser grained and cracked, and contains veinlets filled with magnetite. Chalcopyrite is a minor phase. Disseminated sulphide in this drillhole mostly contains between 2 and 4 per cent nickel. The layer of breccia ore assays 7.2 per cent nickel.

384N DEPOSIT (31°23′25″S; 121°30′50″E)

This deposit is the most northerly in the group, situated 750 m north of the 360N deposit, in a soil-covered area (Fig. 61). It is a category 5 deposit in terms of demonstrated and inferred resources. The deposit occurs on the western, west-dipping limb of the anticline, which here has a core of foliated amphibolite present in subcrop.

Available information suggests that the ultramafic formation is less magnesian overall compared with the area to the south. Rocks of olivine peridotite composition are scarce, and flows of picritic to peridotitic composition dominate. Coarse-grained, bladed to rosetted antinolite-tremolite + biotite rocks are a conspicuous component of the formation, and may represent mafic to ultramafic tuffs (Hough, 1976). In diamond drillhole Z3312 rocks of this type occur over a drilled width of 5 m immediately above the basal contact with foliated amphibolite, and contain an interval (0.4 m thick) of medium-grained pyrrhotite-pentlandite breccia ore and massive to matrix ore. Bladed-textured serpentinized olivine-talc-tremolite rocks, containing low-grade fine-grained disseminated sulphides in the lowermost 2 m, overlie the actinolite-tremolite + biotite rocks.

166N DEPOSIT (21°26′50″S; 121°32′05″E)

The 166N deposit is 2.7 km north of Mount Edwards on the eastern limb of the Mount Edwards anticline in an area with fair outcrop (Fig. 61). It is a category 5 deposit in terms of demonstrated and inferred resources. Triangular-textured ore consisting of 10 to 15 per cent sulphides accounts for most of the mineralization. This is found at or near the base of medium-grained bladed-textured serpentinized olivine-tremolite-talc rocks in contact with amphibolite to the west. More tremolitic rocks with a static metamorphic texture accompany the bladed rocks. Both are overlain by a thin, distinctive unit of komatiitic metabasalt characterized by coarse-grained, subparallel sheaves of actinolite. Further ultramafic rocks overlie this unit.

In diamond drillhole Z5326 triangular-textured ore is underlain by 0.3 m of medium to coarse-grained massive ore, which is separated from the amphibolite by 2.5 m of barren tremolitic rock.

The surface strike length of the deposit is about 120 m. The deposit is limited to the north by a small east-trending fault.

132N DEPOSIT (31°27′35″S; 121°32′25″E)

This deposit is 1 km southwest of 166N deposit, and is located in the axial region of a small, steeply north-plunging syncline on the western limb of the Mount

Edwards anticline (Fig. 61). In terms of contained nickel, the deposit is similar in size to 166N and 384N deposits, but is of lower grade. It is a category 5 deposit.

Disseminated and triangular-textured sulphides with lenses or veins of matrix, massive or breccia sulphides, occur over a strike length of some 250 m in the tongue of ultramafic rocks formed by the syncline, which plunges northwards at about 80 degrees. Bladed to mottled-textured serpentinized olivine-talc + tremolite rock and finer grained, statically recrystallized more tremolitic rocks contain the mineralization, which is at or close to the basal contact of the ultramafic formation. The amphibolites marginal to and along strike from the deposit have a subvertical foliation.

14N DEPOSIT (31°29′30″S; 121°32′00″E)

The 14N deposit is 2 km south-southwest of Mount Edwards, west of the disused railway line from Coolgardie to Widgiemooltha (Fig. 61). The area is one of poor outcrop and is located on the western limb of the Mount Edwards anticline. Estimated demonstrated and inferred resources place the deposit in category 6.

The mineralization is made up of fine-grained disseminated and triangular-textured sulphides enclosed by bladed-textured, partly serpentinized olivine-talc-tremolite rocks. The host ultramafic unit is of olivine-peridotite composition and is at least 50 m thick. Weakly mineralized or barren, more tremolitic rock up to a few metres thick may be interposed between the mineralization and the basal ultramafic-amphibolite contact. A layer of foliated pyrrhotite + pentlandite breccia ore 20 cm thick occurs on the contact in diamond drillhole Z10717. The mineralized zone in this drillhole is 6 m thick and consits mainly of disseminated sulphide which contains between 2 and 3 per cent nickel and is typified by a static metamorphic texture.

SPARGOVILLE GROUP

GEOLOGY

The nickel deposits of the Spargoville group are similar to those of the Mount Edwards group and occur in a direct strike continuation of the same anticlinal zone of mafic to ultramafic rocks (Fig. 61).

Since early 1966, exploration in the area has been carried out by Selco. Four deposits were found near ultramafic-mafic rock contacts and a shaft was sunk at the largest deposit, Location 3 (or 5D), which produced nickel ore in the period 1975 to 1979. A decline was driven into another smaller deposit (Location 2 or 5B) but the arsenic content of the mineralization caused a suspension of production plans in 1971.

The stratigraphy is equivalent to that already described for the Mount Edwards area (Table 36) and is not repeated here. The ultramafic formation (unit 3d in Table 36) is equivalent to Sequence 3 of Gemuts and Theron (1975). Siliceous clastic metasediments and felsic metavolcanic rocks are in direct contact with the ultramafic formation in most areas, and appear to overstep the ultramafic to be in contact with the footwall amphibolite (unit 3c in Table 36) in the north. Strike faults may also be partly responsible for his effect. The same ultramafic formation is repeated by folding and faulting of the mineralized sequence (Fig. 61). Two additional belts of ultramafic rocks occur to the west (Fig. 27), but they appear to be devoid of nickel mineralization.

The style of regional metamorphism is similar to that described for the Mount Edwards group, but the grade may be a little higher, at middle to high amphibolite facies (Barrett and others, 1977). The petrology of the mafic and ultramafic rocks at Spargoville is comparable with that described for the Mount Edwards area (Table 37). The commonest rock types in the ultramafic formation are (a) tremolite/actinolite-chlorite ∓ olivine/serpentine, and (b) metamorphic olivine/serpentine-talc + chlorite + tremolite/anthophyllite + dolomite or magnesite. Spinifex or quench textures are present in some tremolite-chlorite rocks, but otherwise static metamorphic textures (e.g. porphyroblastic, mottled (ovoid) or bladed-olivine textures) prevail, with the local development of either dynamic textures, or static metamorphic textures overprinted on earlier dynamic textures. Lithological alternations, vertical variations in magnesia content, and the presence of sulphidic metasediments indicate that the ultramafic formation is dominantly made up of flows. Units are generally more magnesian towards the base of the formation and range in thickness from a few metres up to perhaps 100 m. The units of olivine peridotite composition are lenticular and generally restricted to the base of the formation. Outcrop over the ultramafic rocks is generally poor, whereas the amphibolites are well exposed and form a low strike-ridge which dies out near the southern boundary of the group.

The structure of the area appears to be dominated by two north-striking, doubly plunging anticlines which are arranged *en echelon* (Fig. 61). A strike fault separates the structures and reduces the extent of ultramafic rocks between the cores of amphibolite. The dip of the layering, and of the metamorphic foliation, which is subparallel to the layering, is commonly between 65 and 85 degrees to the west, although easterly dips are present locally. This indicates that the axial surfaces of the major anticlines are probably inclined westwards.

Sub-concordant tabular intrusions of albite-quartz porphyry with metasomatic margins of biotite and chlorite are common in the basal part of the ultramafic formation at Location 3. Easterly striking doleritic dykes of presumed Proterozoic age transgress the earlier structures.

MINERALIZATION

GENERAL

The deposits were discovered in 1966-1967 by Selco as a result of a combined programme of geological mapping, airborne and ground magnetic surveys, and soil geochemical surveys (Andrews, 1975). The initital indications of mineralization were from nickel and copper anomalies defined by the soil sampling. Gossans were found close to the anomalous soil samples.

Nickel mineralization is confined to the basal 30 m of the ultramafic formation and is associated with metamorphosed unit of overall olivine peridotite composition which are up to 50 m thick. However, the actual host rocks are conspicuously less magnesian than olivine peridotite and consist of tremolite/anthophyllite- talc-serpentine/olivine ∓ chlorite ∓ carbonate rocks of peridotite composition (*cf.* Hancock and others, 1971). The host rocks are foliated or exhibit static metamorphic textures which may be superimposed on an earlier dynamic metamorphic texture.

Structural control of the distribution of mineralization is evident in the form of embayment structures or depressions in the basal ultramafic-amphibolite contact (O'Driscoll, 1971; Andrews, 1975). Sulphidic metasediments are commonly found on the basal contact along strike from the nickel deposits. The general style of mineralization is comparable with deposits of the Mount Edwards and Widgiemooltha groups. However, the largest deposit, which is at Location 3 (about 17 000 t contained nickel), attains only the size of the second order deposits in these other groups. The remaining deposits at Locations 1A, 2 and 5A contain between 1 000 and 9 000 t of nickel each.

The mineralization occurs as ribbon-like to lens-shaped concentrations of mixed disseminated, matrix and massive sulphides which have strike lengths in the range of 50 to 300 m and an average thickness of about 5 m. Fine-grained disseminated sulphides account for most of the mineralization, but thin, irregular layers of foliated massive sulphides are a major component of some shoots and are more abundant than in the Mount Edwards deposits to the south. Massive sulphides are generally medium to coarse grained without conspicuous mineralogical layering or wallrock inclusions, and are found at the base of, or within, disseminated sulphides, and as veins offset into amphibolite or barren ultramafic rock.

Pyrrhotite and pentlandite are the chief primary sulphide minerals accompanied by minor pyrite and chalcopyrite Gersdorffite and niccolite are minor phases in the Location 2 deposit. Mean Ni:Cu ratios are between 11 and 12.

LOCATION 3 DEPOSIT (31°20′55″S; 121°29′50″E)

General

Location 3 (or 5D) deposit is 4.5 km northwest of Mandilla homestead and 20 km southwest of Kambalda, and is sited on the western limb of an anticlinal structure (Fig. 61). Much of the data on which this account is based has been kindly supplied by J. McDonald of Selcast Exploration Limited, the former operators of the mine.

There is gossanous expression of the southern (3 shoot) and northern (4N Hangingwall?) parts of the deposit, but not of the large, central section of the deposit. Eight gossan samples have the following mean composition (standard deviation in parentheses): nickel content is 3 706 ppm (1 823), copper content is 767 ppm (610) and the zinc content is 160 ppm (120). Three of these samples contain up to 0.13 ppm palladium and 0.04 ppm platinum.

Exploratory diamond drilling commenced in 1968 and some 34 drillholes totalling about 10 000 m plus later evaluation drillholes were used to estimate demonstrated and inferred resources of 650 000 t averaging 2.47 per cent nickel (16 055 t contained nickel). Shaft sinking began in May 1971 and the shaft was completed to a depth of 388.3 m in December, 1973. Underground development of four levels at depths between 65 and 230 m below the surface took place in 1974. Concentrates were first produced from ore carted to the N. Kalgurli plant at Boulder in early 1975. From June 1978 onwards ore was carted to the WMC concentrating plant at Kambalda for treatment. Production to the end of 1978 has amounted to ore and concentrates containing 7 842 t of nickel (Table 2). In its final state the mine was developed on six levels with the deepest (no. 11) level being 330 m below the surface. Remaining resources below the 11 level do not appear to be great. The largest, central-north section of the deposit (2 shoot and North Cut and Fill) appears to terminate about 50 m below the 11 level. The small, but high grade 3 shoot continues at least to 120 m below the 11 level, but would be uneconomic to mine alone. Production ceased and the mine closed at the end of 1979.

Stratigraphy

The ultramafic formation is between 100 and 150 m thick. The formation is underlain to the east by foliated, pillowed amphibolite and overlain to the west by a thin unit of amphibolite which is in turn succeeded by clastic metasediments (Fig. 61). Metamorphosed olivine peridotite and peridotite are largely restricted to the basal 50 to 60 m of the ultramafic formation, the upper part of the formation being made up mainly of tremolite-chlorite rocks (meta-picrite). The olivine peridotite and peridotite units are 10 to 40 m thick and are lenticular along strike and down dip. These units are represented by mottled and rarer bladed-textured olivine/serpentine-talc + tremolite/anthophyllite rocks, and tremolite-talc-olivine/serpentine + chlorite rocks. The ultramafic rocks generally lack a distinct metamorphic foliation.

The footwall amphibolite contains green-brown hornblende and calcic plagioclase and, though foliated, is characterized by an overprinted static metamorphic texture of hornblende. Flattened pillowed structures are common and some pillows exhibit felsic cores and variolitic margins. At the contact with the ultramafic formation the footwall amphibolite is more coarsely recrystallized into interlocking prisms or rosettes of hornblende or pale amphibole. Chloritic or biotitic metasomatic reaction-zone material appears to be rarely developed at this contact, but is common on contacts between quartz-feldspar (albite) porphyry intrusions and ultramafic rocks.

Fine-grained, laminated metasedimentary rocks consist of quartz, albite, pale amphibole, chlorite, graphite and carbonate, and variable amounts of pyrrhotite with minor chalcopyrite or sphalerite (Wilmshurst, 1975). The metasedimentary horizons are commonly less than a metre thick, and are found on the basal ultramafic-amphibolite contact within 10 to 30 m of the edges of the nickel deposit.

Some metasediments have a possible reconstituted fragmental texture and may be metamorphosed felsic tuffs.

General structure

The mafic to ultramafic sequence dips west at about 70 degrees, but is locally overturned. The basal ultramafic-amphibolite contact delineates a shallow embayment structure (O'Driscoll, 1971), which is apparently not defined by faults in the way that has been described for similar structures in the Kambalda area. The embayment is up to about 300 m in strike length and extends to a depth of at least 350 m. Most of the mineralization appears to be contained within this embayment (Fig. 62), and accordingly the overall dimensions of the deposit are related to it. A longitudinal section through the deposit indicates a steep plunge to the south-southeast at 75 to 80 degrees (Fig. 63). Sub-horizontally plunging flexural folds deform the shoot but appear to be post-dated by northerly striking faults. Laminated sulphidic metasedimentary rocks are present on the basal ultramafic-amphibolite contact immediately along strike from the deposit (Fig. 63). The southern part (3 shoot) of the deposit persists to at least 450 m depth, and a surface diamond drillhole intersected important mineralization at a depth of 600 m.

Ore distribution and structure

The distribution of nickel mineralization in terms of thickness times per cent nickel in drillholes and underground openings is shown in Figure 63. The 5 metre – per cent contour line outlines three principal shoots termed from

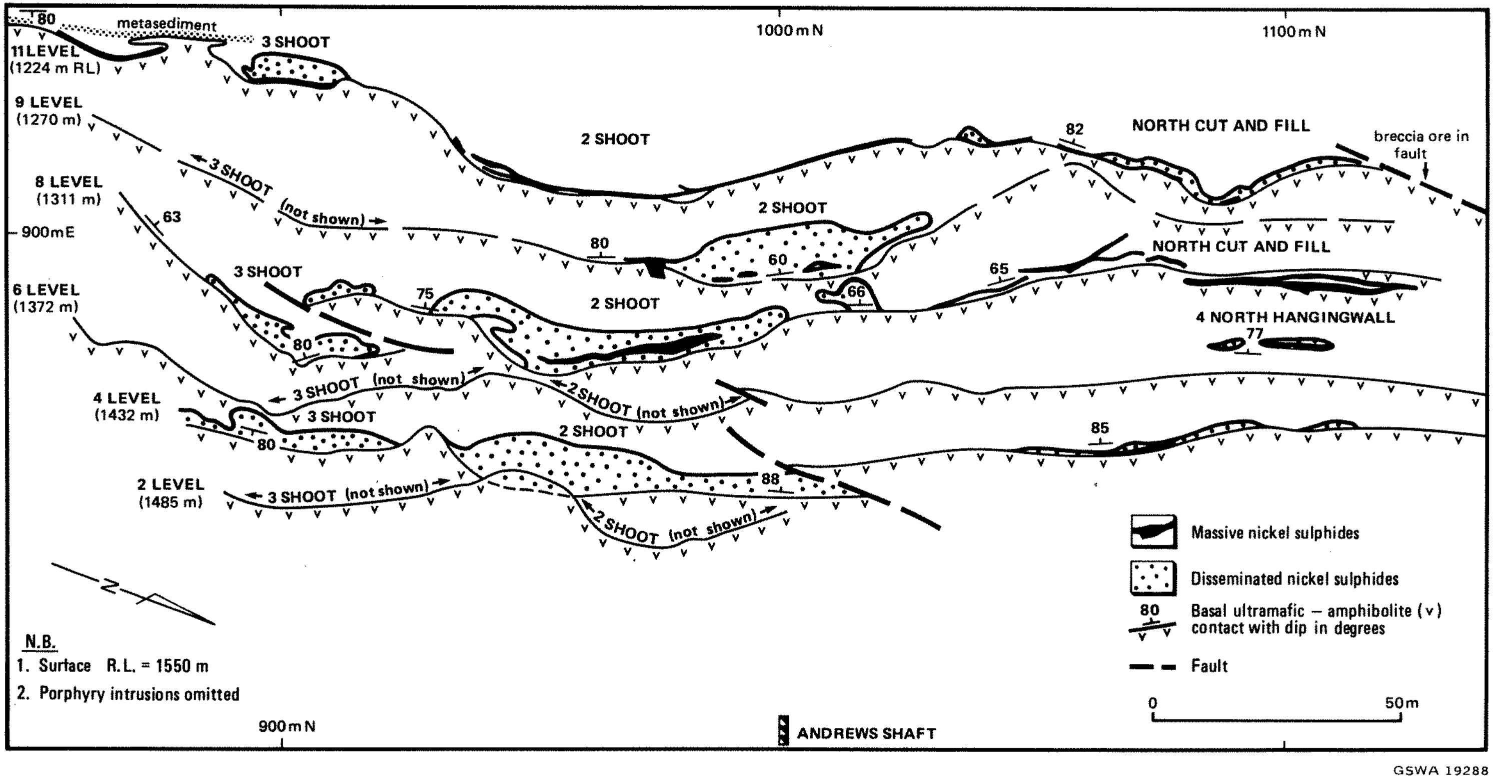

Figure 62. Composite plan of the basal ultramafic-amphibolite contact at Location 3 mine Spargoville, with the distribution of mineralization indicated as intersected during level development (data from Selcast Exploration Ltd).

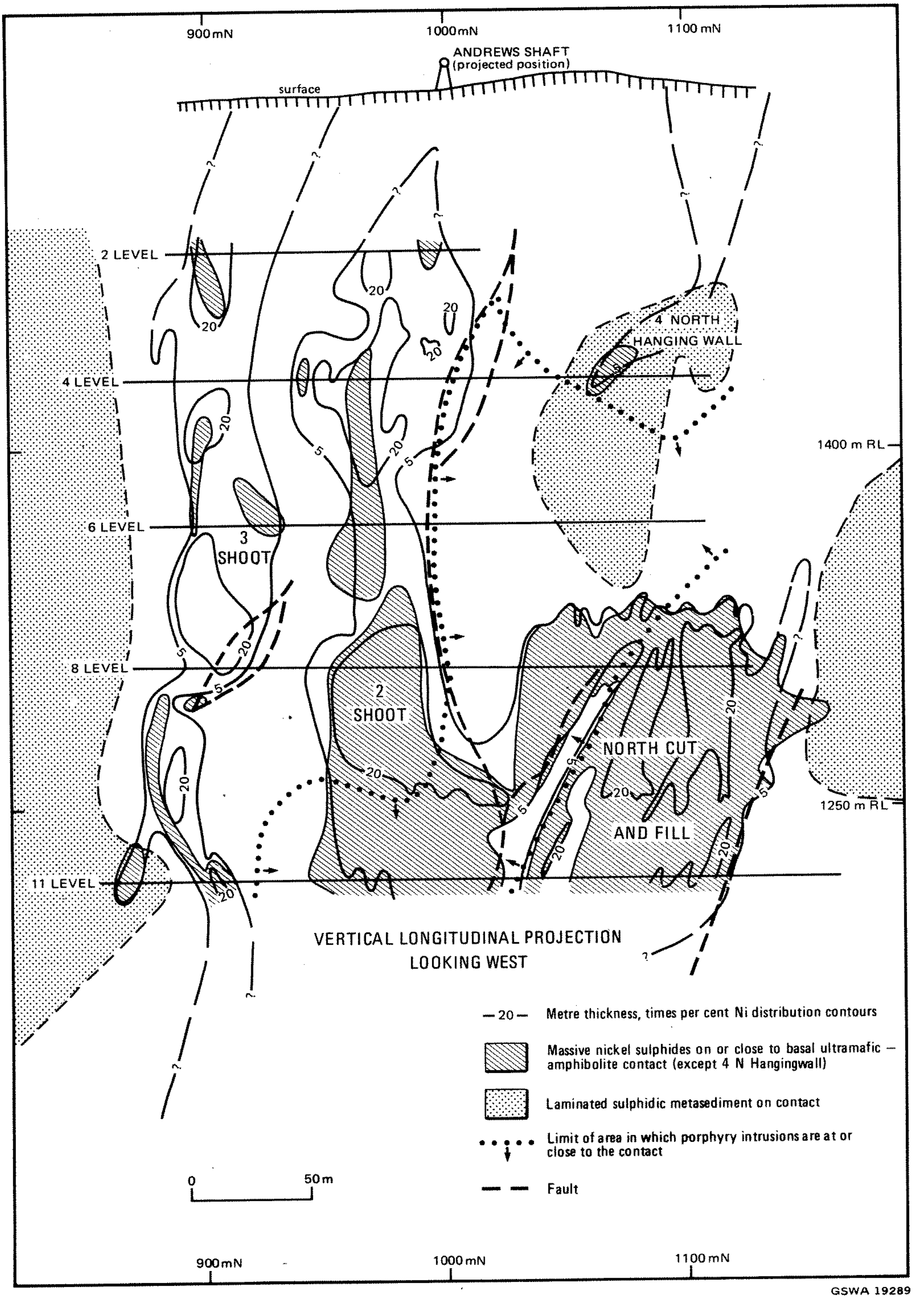

Figure 63. **Vertical longitudinal section projection of Location 3 deposit, Spargoville, showing the distribution of nickel ore, and of metasediment and porphyry intrusions in the contact zone (data from Selcast Exploration Ltd.).**

south to north 3 shoot, 2 shoot and North Cut and Fill. These three shoots consist of contact mineralization which is in part offset into the adjacent ultramafic rock or amphibolite. A small body of hangingwall mineralization occurs 15 to 20 m stratigraphically above the basal ultramafic-amphibolite contact on the basal contact of the second ultramafic flow unit. This body has been opened up from the northern end of the 4 level and is referred to as 4 North Hangingwall. It consists of lenses of coarse-grained, weakly layered massive sulphide within more continuous disseminated-to-matrix sulphides.

The 3 shoot orebody is the most persistent part of the deposit, and drilling indicates that it continues to at least a depth of 450 m below surface. However, the strike length of the shoot is less than 50 m and most mineralization consists of disseminated-to-matrix sulphides, though massive sulphides may increase in proportion at depth (Fig. 63). A structural high in the basal ultramafic-amphibolite contact separates 3 shoot from 2 shoot. At the southern end of the 11 level a laminated pyrrhotitic metasedimentary horizon overlaps a subsidiary lobe of the shoot which occupies a small depression in the contact (Figs 62 and 63). Although the metasediment is parallel to porphyry intrusions and appears to be partly spatially associated with strike faulting, the relationship may be analagous to that described for part of Ken shoot at Kambalda. This relationships involves an interpretation that a sediment was deposited over a primary depression in the topmost basalt surface, the depression having already been filled with an ultramafic flow and its basal nickel sulphides.

The 2 shoot and North Cut and Fill orebodies are more or less continuous at depth where their combined strike length is 200 m. Above the 10 level, 2 shoot resembles 3 shoot but is generally distinguished by a thicker mineralized section which contains a higher proportion of massive sulphides. Much of the massive sulphide in the lower part of the shoot occurs as off-contact lenses up to a few tens of centimetres thick within disseminated ore (Fig. 64A). A similar distribution of massive sulphide is seen in North Cut and Fill (Fig. 64B). The adjacent parts of 2 shoot and North Cut and Fill are intimately associated with massive or weakly foliated felsic porphyry intrusions which were emplaced sub-parallel to the contact (Fig. 63) and subsequently deformed. In ultramafic rocks the margins of these intrusions are marked by thin metasomatic reaction zones of chloritic schist which may be the locus for coarsely recrystallized massive sulphides occurring as lenses of very irregular thickness. Veins of massive sulphide also cross cut porphyry.

Massive sulphides are displaced into the footwall amphibolite in North cut and Fill at and above the 8 level (Fig. 63) and along the faulted northern margin of the shoot. Much of the amphibolite here is coarsely recrystallized into stout laths or rosettes of hornblende, and the massive sulphides tend to be coarser grained (3 to 5 mm) and more nickel-rich than normal contact ore. Veins of massive sulphide up to 5 m thick penetrate the footwall and amphibolite in lower 2 shoot and North Cut and Fill; the mineralogical layering, which normally is parallel to the margins of contact ore, shows a 'sinkhole effect' in curving downward into the vein where the vein meets the contact ore.

Ore petrology

Primary nickel ore consists of monoclinic and minor hexagonal pyrrhotite (Hancock and others, 1971) and pentlandite with minor to accessory pyrite, smythite (Ramsden, 1975), and chalcopyrite, and accessory magnetite and chromite. The mean Ni:Cu ratio is 10.7. The oxidized zone extends to 70 m depth and the base of the transition zone is at about 120 m depth. Primary massive ore generally assays between 7 and 12 per cent nickel, but this may increase to some 20 per cent where massive ore is entirely within amphibolite. This reflects an increase in pentlandite content and may also be accompanied by coarser scale mineralogical layering and grainsize (e.g. pentlandite 5 to 10 mm in diameter). Pyrite (generally fine grained) and chalcopyrite may be intergrown and are both commonly richer in offset or remobilized ore. Better grade ore is also found in the synclinal portions of the sub-horizontally plunging flexural folds (J.A. McDonald, pers. com., 1978).

The coarse grainsize, general lack of pyrite, and indistinct, coarse mineralogical layering in massive ore contrast with most Kambalda massive ores, but may be compared with Redross ores. A fine-scale foliation defined by oriented gangue inclusions is not conspicuous except in massive or breccia ore in sheared zones (e.g. schistose margins of porphyry intrusions). Some pyrrhotite in massive ore is elongated, but deformation twins or kink bands are rare except in the few samples of remobilized ore examined. An annealed matrix of fine- to medium-grained, strain-free pyrrhotite is more typical of both massive and matrix-disseminated ore. The sulphides in matrix-disseminated ore are finer grained and show static metamorphic intergrowth textures with medium- to coarse-grained metamorphic olivine (or serpentine) and sheaves of slender amphibole prisms. Foliation is only patchily developed. Disseminated to matrix ore contains between 1 and 6 per cent nickel.

Hancock and others (1971) described very fine-grained bleb-like inclusions of pyrrhotite-pentlandite ∓ pyrite in olivine (in subgrade disseminated ore), which increase in size downwards through the mineralized section. Pyrrhotite is reported to contain between 0.24 and 0.65 per cent nickel, whereas pentlandite contains about 28 per cent nickel (Ramsden, 1975).

LOCATION 1A DEPOSIT (31°19′20″S; 121°29′40″E)

Location 1A is 4 km north of the mine at Location 3, near the northern closure of an elongated anticline (Fig. 61). The area is poorly exposed and several costeans were dug to locate the basal ultramafic contact. Gossans after disseminated and massive sulphides occur in pronounced embayment structures in the basal ultramafic-amphibolite contact (Andrews, 1975; Taylor, 1975). Exploration diamond drilling (30 drillholes totalling about 10 000 m) and later evaluation drilling have defined three small shoots with demonstrated resources totalling 365 000 t averaging 2.53 per cent nickel (9 234 t contained nickel), which includes some allowance for mining dilution. The shoots are associated with the basal stratigraphic contact of a lens of steeply west-dipping metamorphosed olivine peridotite. This lens has a strike length of about 500 m and a thickness of up to 160 m attained in embayment structures in the basal ultramafic-amphibolite contact. A thin unit (up to 10 m thick) of tremolitic and chloritic ultramafic rock is commonly present between the stratigraphically overlying more magnesian, bladed, metamorphic olivine + anthophyllite or talc-carbonate-bearing rocks of the lens, and the underlying footwall amphibolite. Dips are steeply southwestwards which result in an overturned stratigraphy. Static metamorphic textures predominate in ultramafic and mafic rocks. The amphibolite preserves pillowed and variolitic igneous textures.

The mineralization appears similar in style and distribution to that described for Location 3. Fine-grained disseminated-to-matrix sulphides containing between 1 and 6 per cent nickel account for much of the mineralization in the ultramafic rocks. Amphibole-bearing varieties of the ultramafic rocks contain some of the mineralization, and thin veins of massive sulphides are present in the footwall amphibolite and in the disseminated to matrix sulphides in ultramafic rocks. Sulphide mineralogy and textures are similar to those at Location 3; details are given by Taylor (1975).

LOCATION 2 DEPOSIT (31°21′20″S; 121°30′00″E)

The deposit is also known as Location 5B, and is situated 1.5 km south-southeast of Location 3 mine, on the western limb of an anticline adjacent to the anticline containing Location 3 deposit (Fig. 61). Outcrop is sparse and the ultramafic rocks tend to be oxidized and

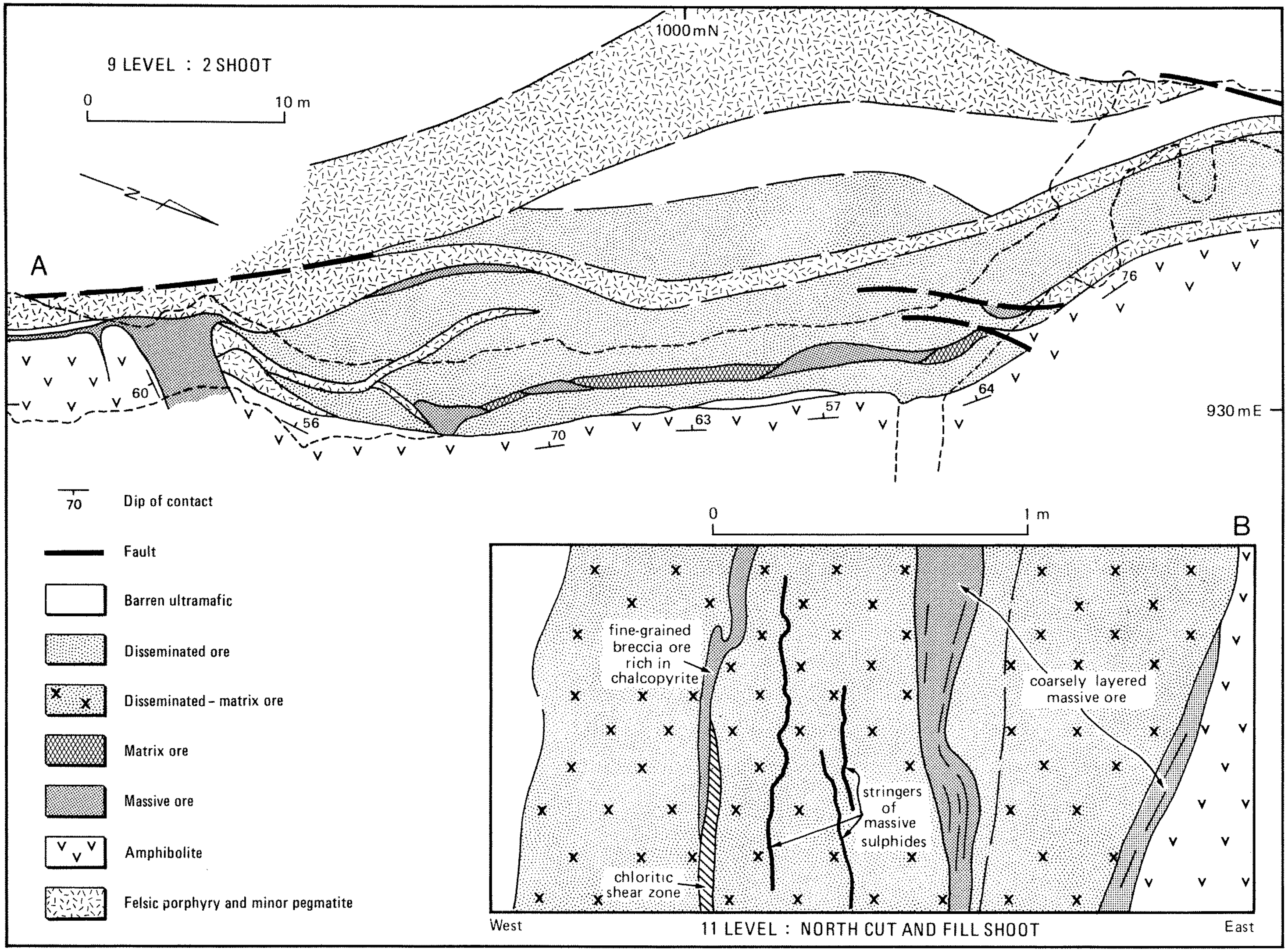

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Figure 64. A. Geological plan of 2 shoot on early 9 level underground openings, Spargoville.
B. Sketch map of the backs in southern 11 level, North Cut and Fill shoot, showing multiple lenses of massive ore, Spargoville.

ferruginized. A discontinuous gossan less than 1 m thick crops out, and a sample analyzed by Travis and others (1976) contained 0.5 per cent nickel, 0.32 per cent copper, 694 ppb palladium and 213 ppb iridium. Exploration diamond drilling (26 drillholes totalling about 5 000 m) and later evaluation drilling have outlined demonstrated resources of 119 520 t averaging 2.32 per cent nickel (2 767 t contained nickel), which includes some allowance for mining dilution.

The basal ultramafic-amphibolite contact dips west at about 75 degrees, and is marked by a thin unit of compositionally layered, fine- to medium-grained, foliated quartz-feldspar-biotite-actinolite metasediment or tuff. Sill-like bodies of feldspar porphyry have intruded the contact zone. The overlying 10 metres or so of ultramafic rocks consist of foliated tremolite + chlorite + carbonate which may contain a few metres thickness of fine-grained disseminated sulphides and veinlets of breccia sulphide. Nickel sulphide stringers are also found in the footwall amphibolite. These tremolitic rocks are succeeded by a lenticular unit of bladed or mottle-textured olivine-talc + tremolite rocks up to about 30 m thick, which may also contain disseminated nickel sulphides. Thin, differentiated flow units of picritic composition overlie this lenticular unit, and some spinifex-textured rocks are found in them. The disseminated sulphides contain up to about 6 per cent nickel and consist of pyrrhotite, pentlandite, and minor or accessory chalcopyrite, pyrite, gersdorffite and niccolite.

According to Andrews (1975) the deposit has a strike length of 120 m, a width of up to 11 m and a down-dip length of 150 m.

LOCATION 5A DEPOSIT (31°20′30″S; 121°30′10″E)

The 5A deposit is 750 m east-northeast of Location 3 mine, and occurs immediately north of the main access road to the mine. The 5A deposit is related to the same anticlinal structure that contains the Location 2 deposit, but is on the eastern limb which here dips steeply to the west. Exploration diamond drilling (24 drillholes totalling about 3 200 m) and later evaluation drilling have defined demonstrated resources of 43 600 t of oxidized and sulphide mineralization averaging 4.74 per cent nickel. The amount of recoverable sulphide ore in this total is estimated at about 25 000 t averaging 5 per cent nickel (1 250 t contained nickel). The deposit seems to represent the residual part of the larger accumulation since removed by erosion. The deposit has a strike length of about 130 m and a down-dip dimension of only 80 m; the upper 30 m is entirely oxidized and the remainder is supergene mineralization (Andrew, 1975).

The stratigraphy of the ultramafic rocks is similar to that described for Location 2 deposit, except that a thick lens of metamorphosed olivine peridotite (with a strike length of some 250 m) occurs near the basal ultramafic contact in the southern section of the 5A deposit. Mineralization is found in foliated tremolitic rocks and more magnesian, statically recrystallized ultramafic rocks. Foliated massive supergene sulphides (violarite-pyrite) are important, and in drillhole WA 5/150 nearly 4 m of such material has nickel contents in the range 12.8 to 16.6 per cent.

COOLGARDIE GROUP

GEOLOGY

The nickel deposits of the Coolgardie group occur to the southwest of the town in terrain dominated by syntectonic and post-tectonic granitoids, which have broken up the supracrustal rocks into small arcuate belts and remnants (Fig. 65). Mafic and ultramafic rocks dominate the supracrustal rock assemblages, and are accompanied by thin units of semi-pelitic metasedimentary rocks, chert, black slate, and felsic metavolcanic or volcaniclastic rocks. The metamorphic grade is generaly amphibolite facies and a dynamic metamorphic texture characterizes many rocks (Binns and others, 1976), although spinifex and pillowed textures are preserved in some.

Gemuts and Theron (1975) and Williams (1976) regarded the mafic and ultramafic rocks as stratigraphically equivalent to those in the Widgiemooltha — Mount Edwards — Spargoville and Kambalda — St Ives areas. Steep dips predominate but in contrast to these areas the strike direction is generally between north and northeast. The internal stratigraphy of the Coolgardie area is not clear. Gemuts and Theron (1975) indicated that the mafic to ultramafic sequence youngs eastwards and southwards, the granitoid body southwest of Coolgardie having been emplaced into the base of the sequence. However, this interpretation may be complicated, at least locally, by the possibility of two generations of major folding. The open, plunging anticline and syncline shown on Figure 65 are the obvious structures, but more appressed folds, such as that outlined by a black slate horizon at Comet Hill, could pre-date the major open folds. Strike faults also hamper geological interpretation.

Muscovite-bearing pegmatite intrusions are present locally on the margins of the supracrustal sequence, notably at Nepean and Londonderry. Discordant Rb-Sr mineral ages indicate that the Londonderry pegmatite was emplaced about 2 700 m.y. ago (Compston and Arriens, 1968; Turek and Compston, 1971).

MINERALIZATION

GENERAL

The deposits all occur at or near the structural (and probably stratigraphic) base of lenticular host units of metamorphosed olivine peridotite in contact with amphibolite of tholeiitic composition. Spinifex-textured rocks of picritic composition are present in the hangingwall sequence but it is not clear whether the ultramafic hosts are intrusive or extrusive rocks. The host rocks are thoroughly reconstituted texturally and the most characteristic nickeliferous rock consists of a network of ovoid to bladed-textured metamorphic olivine (commonly retrogressively serpentinized) with interstitial nickel sulphides and talc. This relationship gives rise to the term 'triangular-textured ore' where the olivines form elongate prisms in a sulphide matrix. Massive sulphides are a minor component of the mineralization and bear no consistent relationship to the remainder of the ore section. The dominant primary sulphide assemblage is pentlandite-pyrrhotite + chalcopyrite ∓ pyrite, and a high pentlandite:pyrrhotite ratio results in high nickel tenors for the sulphide fraction. Nickel-rich sulphides such as millerite, heazlewoodite and awaruite occur in some sulphide-poor disseminated ores. The high metamorphic grade and dynamic style of recrystallization have had important effects on the distribution and petrology of ore (Barrett and others, 1976).

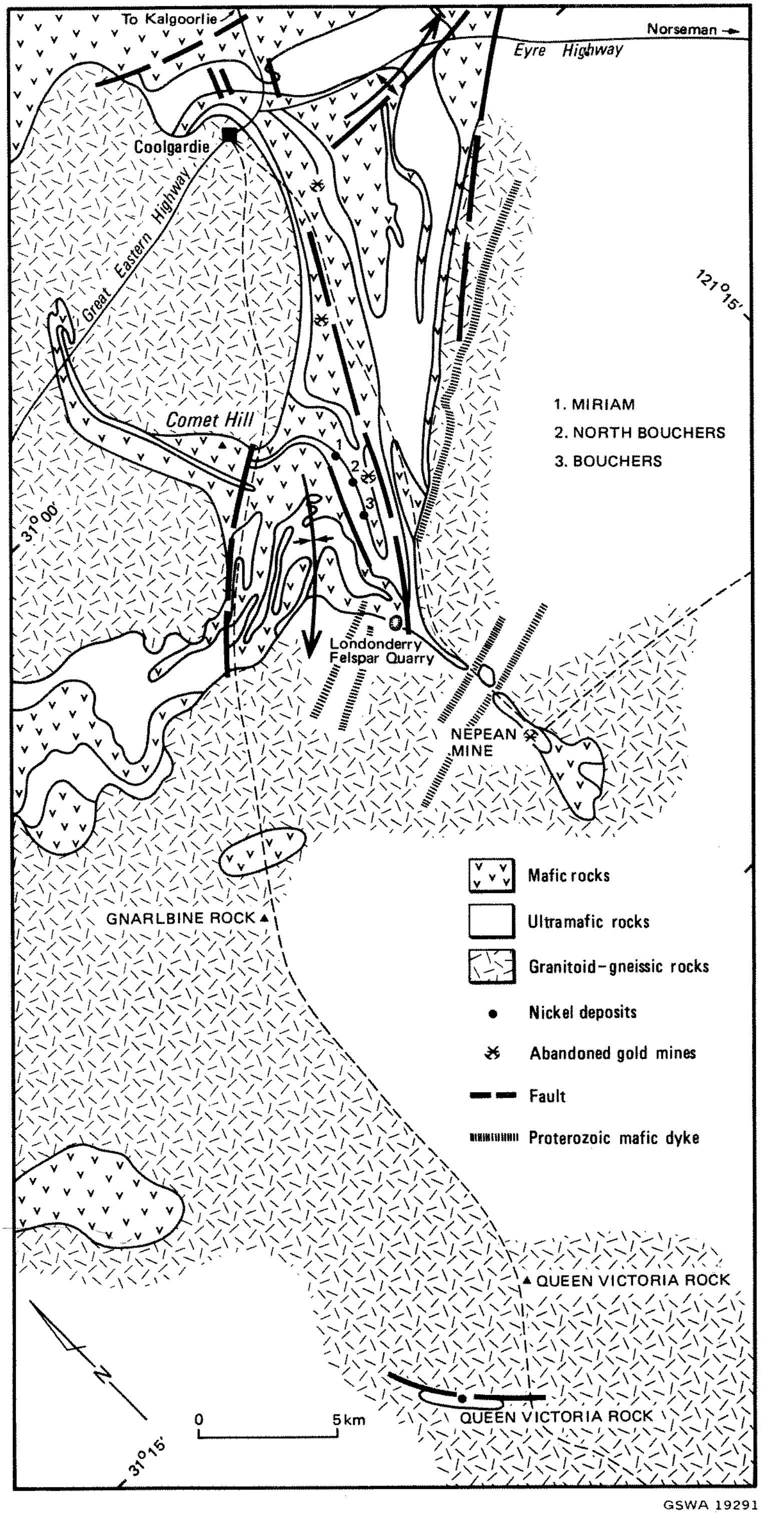

Figure 65. Geological map of the Coolgardie group of deposits (mainly after Gemuts and Theron, 1975).

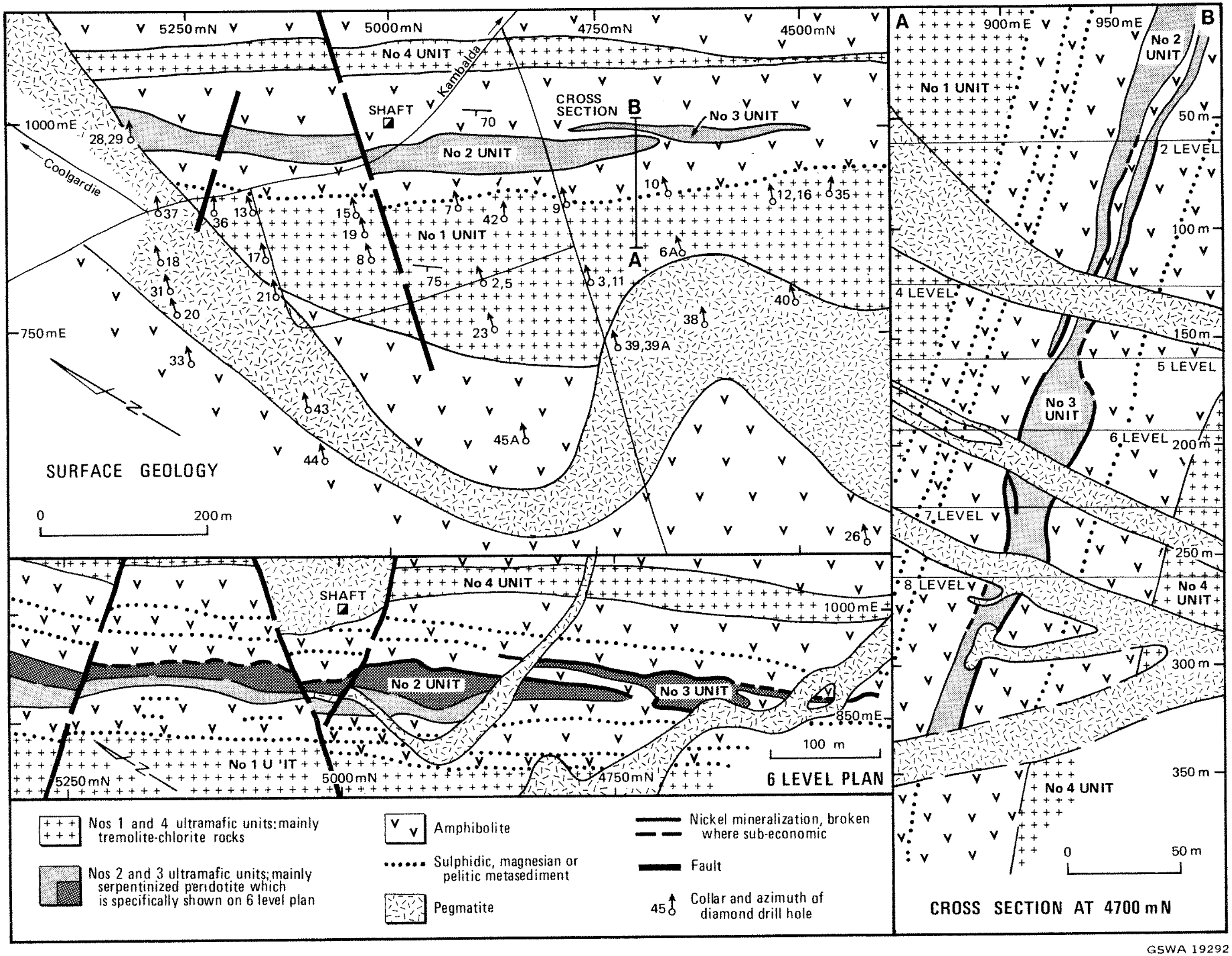

Figure 66. Surface geology (interpreted subcrop), 6 level geological plan, and cross section through the Nepean deposit (date from Metals Exploration NL).

Exploration in the late 1960s, carried out mainly by Anaconda and Metals Ex, was based on the model of the newly discovered Kambalda type of nickel deposit. This required intense prospecting of the basal contacts of ultramafic units but, in contrast to Kambalda, the discovery of gossans did not play a role in the finding of the two principal deposits in the Coolgardie group (Nepean and Miriam). Nepean is the only known deposit of commercial importance, and it has maintained a modest but steady production for ten years. The average ore grade of 4 per cent nickel is high enough to compensate for the cost of mining the narrow, irregular and steeply dipping mineralization. The tonnage and average bulk tenor of the known mineralization at Miriam is too low to be economically extracted, and deep supergene alteration is another inhibiting factor. The remaining deposits appear to be small and isolated.

NEPEAN DEPOSIT (31°09′10″S; 121°04′30″E)

General

The Nepean deposit is 26 km south-southwest of Coolgardie in the largest remnant of a fragmented southern appendage to the main belt of supracrustal rocks (Fig. 65). The deposit was discovered in March 1968 by diamond drilling conducted by Metals Ex., (in joint venture with Freeport) although gossan was absent at the discovery site (Sheppy and Rowe, 1975). Outcrop is of poor quality and is sparse. The successful diamond drillhole (ND 3) was inititally designed to test magnetic and induced polarization anomalies related to an ultramafic unit (No. 1) and an associated sulphidic metasedimentary horizon (Fig. 66). Deepening of the drillhole intersected another ultramafic unit (No. 2) which contained nickel sulphides on its basal (eastern) contact. Further drilling along strike to the south encountered another unit (No. 3), *en echelon* to No. 2, and also having mineralization, but, in places, on both eastern and western contacts. A small gossan was found during costeaning across the contacts of the ultramafic units, and three samples analyzed by Travis and others (1976) contained an average of 0.28 per cent nickel, 0.07 per cent copper, 104 ppb palladium and 15 ppb iridium.

Initital ore reserves were estimated at between 400 000 t and 500 000 t averaging a little over 4 per cent nickel (say 18 000 t contained nickel). Shaft sinking began in February 1969, and following an agreement with WMC the first ore was carted for treatment at Kambalda in January 1970. Annual production of nickel contained in ore treated has averaged a little over 2 000 t (Table 2) Using a 1.5 per cent nickel cut-off figure, the indicated and inferred mining reserves (above the 12 level at 417 m depth) in 1979 amounted to 240 000 t averaging 3.9 per cent nickel (9 630 t contained nickel). By 1980 these reserves had declined to 7 134 t of contained nickel. Irregularity in thickness and grade of the orebody have precluded reserve estimations in the measured category. A further 53 000 t (1980) of potential ore is inferred to exist below the 12 level to a depth of about 550 m. The deepest drillhole intersection of mineralization is at a depth of 475 m (ND 45A). Development drilling is required to improve the status of this potential ore. Extraction of the deep mineralization will be via 1 200 m of decline driven from the 11 level. The mine is presently developed on ten levels, the deepest being the 12 level at 417 m. Mining is conducted by cut and fill stoping using hydraulically placed sand fill. In June 1979 Metals Ex. purchased Freeport's half share of the ownership of the mine. The State Government granted the company a development loan for the mine in October 1979.

Stratigraphy

The Nepean nickel deposit occurs at the northern end of a large supracrustal remnant in granitoid rocks (Fig. 65). The remnant has a strike length of about 8 km, is up to 2 km wide, and consists mainly of amphibolite derived from basalt and gabbro. Thin conformable units of ultramafic rocks, metasediments and felsic porphyry are present in the amphibolite. The layering and a parallel metamorphic foliation are vertical or dip steadily westwards. The strikes in the western half of the remnant are linear and northerly, whereas in the east several north-plunging folds produce arcuate strikes. Sheppy and Rowe (1975) proposed that a fault separates these two tectonic domains. Intrusions of pegmatite, aplite, granitoid and mafic porphyry transect the layering and foliation at a high angle in many places. Nepean occurs in the western, linear domain, which may be isoclinally folded, although there is no direct evidence for this. The general stratigraphy is therefore uncertain, but in the mine area petrological profiles through the ultramafic units and the distribution of nickel mineralization indicate that the layering faces westwards.

The ultramafic units in the mine area have been numbered 1 to 4 from west to east (Fig. 66) by Sheppy and Rowe (1975). Units 1 and 4 are of overall picritic composition and are about 150 and 45 m thick respectively. They consist of numerous sub-units (each about 10 to 15 m thick, and some being spinifex-textured) of tremolite-chlorite rock grading downwards (eastwards) into porphyroblastic metamorphic olivine/serpentine-tremolite-chlorite rock (Barrett and others, 1976). Units 2 and 3, the hosts to mineralization, are dominantly made up of serpentinite. The bulk olivine peridotite composition (36.0 to 40.7 per cent MgO) (Groves and Hudson, 1981) and the internal petrological zonation of Units 2 and 3 are similar, and suggest that they represent one or more komatiitic flows. Barrett and others (1976) recognized the following zones in unit 2, all but zone (1) being also found in unit 3. The olivine is of metamorphic origin and is partly serpentinized.

Top (west) (1) chlorite-tremolite with olivine (Fo_{76-82}) porphyroblasts increasing in size and abundance downwards

(2) chlorite-tremolite with spinifex texture at top and olivine at base

(3) quartz-pyrrhotite-chalcopyrite-sphalerite ∓ actinolite metasediment, or amphibolite, or a copper-zinc enriched ultramafic rock

(4) olivine (Fo_{90-95})-chlorite-tremolite-magnesio-cummingtonite(?) ∓ anthophyllite ∓ diopside ∓ enstatite/talc: the olivine is more abundant downwards and forms bladed prisms in the upper ore section (triangular-textured ore) and smaller sub-equant grains in the generally underlying, more sulphide-rich matrix ore.

Zones (1), (2) and (4) demonstrate a clear trend of downward enrichment in magnesia, which is consistent with the structural base of units 2 and 3 being coincident with their stratigraphic base. Static metamorphic textures characterize most ultramafic rocks, though much of unit 4 is schistose.

The amphibolite is fine to coarse grained, massive or foliated and contains green-brown hornblende, cummingtonite and calcic plagioclase with minor quartz and biotite. Diopside and clinozoisite occur near contacts with ultramafic rocks. Hornblende commonly displays a strong static metamorphic growth superimposed on the foliation or layering. Chemical data indicates a tholeiitic composition (Barrett and others, 1976). The same authors described the mineralogy of thin (0.5-3.0 m) metasedimentary horizons in the sequence (Figs 66 and 93A) as follows:

(a) laminated quartz-pyrrhotite plus plagioclase, microcline, diopside, tremolite, chlorite, biotite, cordierite, siderite, tourmaline, graphite and sphalerite;

(b) foliated magnesian rocks containing cordierite, anthophyllite and cummingtonite;

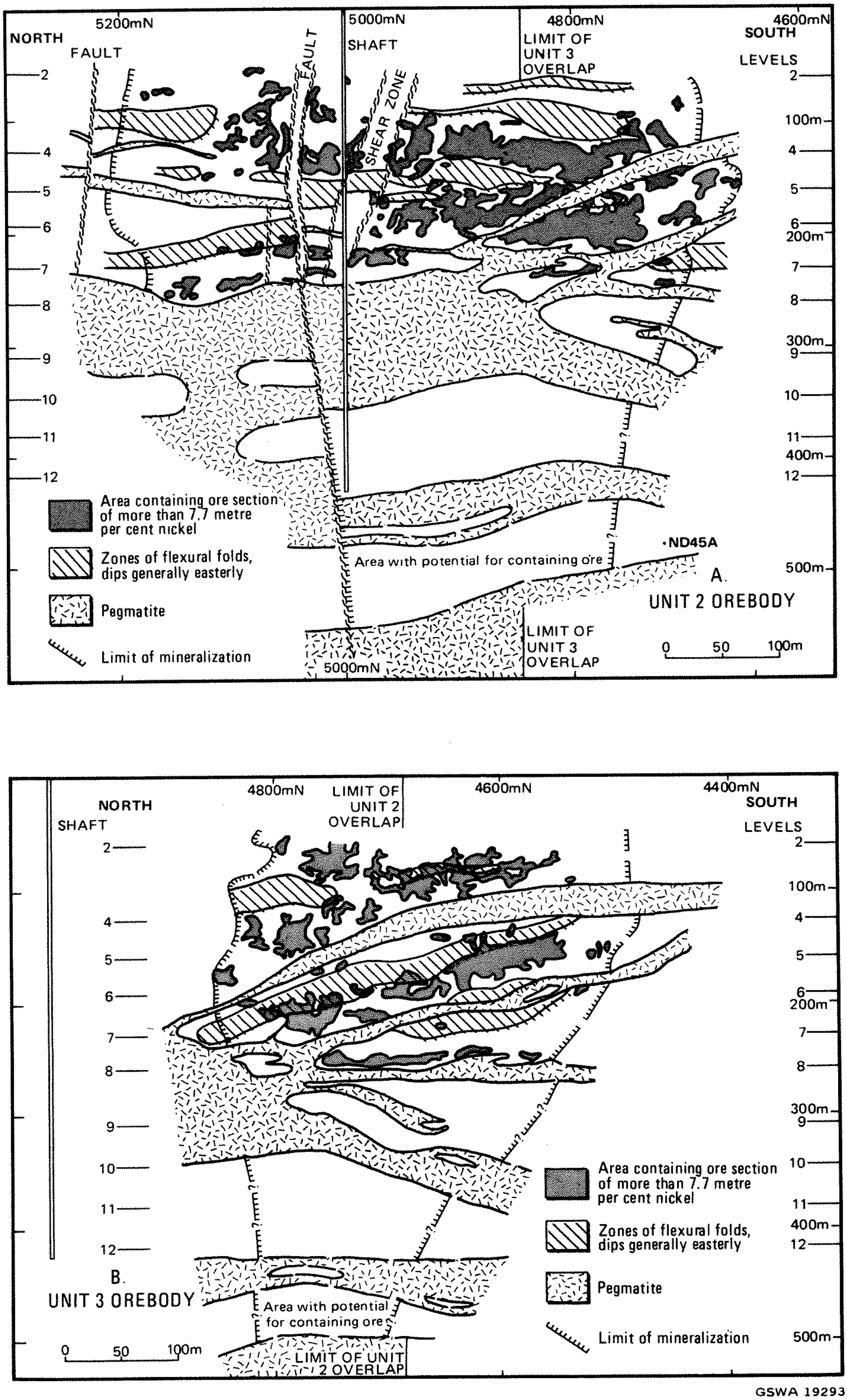

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Figure 67. Vertical longitudinal section projections (looking east) of the Nepean deposit showing the distribution of (i) nickel mineralization (ii) thicker and/or higher grade ore sections (iii) sub-horizontal flexural folds and (iv) pegmatite. A = Unit 2 ultramafic orebody, B = Unit 3 ultramafic orebody (data are from Metals Exploration NL and are confined to 8 level and above for (ii) and (iii)).

(c) foliated pelitic rocks containing biotite, almandine, plagioclase, quartz, sillimanite, staurolite and rare andalusite.

Metasomatic reaction zones containing rosetted pale amphibole, biotite or chlorite are common on contacts between (i) ultramafic rocks of units 2 and 3 including matrix-disseminated or triangular-textured ores, and (ii) amphibolite or pegmatite. The pegmatites contain quartz, albite, microcline and muscovite plus accessory almandine, molybdenite, sphalerite and galena.

The mineral assemblages in the amphibolite and the pelitic and ultramafic rocks indicate that prograde regional metamorphism attained conditions of 650 to 700°C and 300 to 500 MPa (Barrett and others, 1976). The replacement of metamorphic olivine and enstatite by serpentine and talc respectively is probably a retrogressive effect.

General structure

In the area of the deposit, the strike is mainly north-northwest and the dip is commonly westerly at about 70 degrees. However, local changes in strike and reversals in dip (Fig. 66) are attributed to flexural folding along sub-vertical and sub-horizontal axes respectively (Sheppy and Rowe, 1975). The sub-horizontal folds are common and they influence ore distribution (Fig. 67). Important sub-vertical flexuring is restricted to the vicinity of the shaft, where it is associated with a shear zone which offsets the sub-horizontal flexures but apparently does not transect pegmatite (Fig. 67A). East and northeasterly trending faults displace the sequence abruptly and also cut pegmatite. Most pegmatite forms gently east-dipping, sill-like intrusions which displace rather than replace the stratigraphy and are therefore dilational.

The similarity of ultramafic units 2 and 3 has been referred to above. This similarity, the thinness of unit 3 in the area of overlap with unit 2, and the high ratio of sulphide to overlying serpentinite thickness in the overlap area led Barrett and others (1976) to suggest that the units could have originally been a single ultramafic body. They postulated that separation of the units into their present disposition was achieved by sinistral strike-slip faulting with an east-side-up component of movement. Strike-slip movement of about 130 m is required to restore the proposed former continuity of the basal (eastern) contacts of units 2 and 3. The contrary view is that the two units, though genetically related, were emplaced (either as flows or intrusions) separately and penecontemporaneously (Sheppy and Rowe, 1975). Evidence in favour of the separate emplacement hypothesis is as follows:

(a) in underground openings the two ultramafic units are never observed to join (Sheppy and Rowe, 1975; B.L. Kirkpatrick, pers. comm., 1978);
(b) the northern end of the basal ore section in unit 3 is directly along strike (less than 100 m apart on 4 level drive) from a laminated pyrrhotitic metasedimentary horizon in amphibolite;
(c) this metasedimentary horizon appears to be a consistent distance stratigraphically below unit 2, and is underlain by a further metasedimentary horizon which , however, appears to be the only horizon in the amphibolite below unit 3 (Fig. 66).

Relationship (b) is common in volcanic peridotite-associated nickel deposits where it is regarded as an original feature. Temporally and spatially overlapping basic and ultrabasic volcanism may account for the observed overlapping relationship between units 2 and 3 (cf. Ken shoot, Kambalda). The separate emplacement hypothesis is preferred to the structural interpretation of Barrett and others (1976).

Ore distribution and structure

The deposit has a near-surface strike length of about 730 m, and appears to continue to a depth of at least 475 m. The deposit is divided into the overlapping 2 and 3 orebodies, contained in the unit 2 and 3 ultramafics respectively (Fig. 66). The orebodies have a vertical or steep southward plunge and may taper with depth (Fig. 67). The bulk of the mineralization is on the basal (eastern) contacts of the ultramafic units, but a small amount (referred to as hangingwall ore) occurs on the top contact of unit 3 and is locally continuous with basal contact ore at the southern end of unit 2 (e.g. 8 level stopes). Some ore also continues south beyond the limit of the basal contact of unit 3, and for up to 50 m is entirely within foliated amphibolite.

The average thickness of the ore section is about 1.2 m, but the actual thickness may vary abruptly within a few metres of strike. The thicker and/or better grade ore sections are generally not coincident with either the sub-horizontal flexures or the sub-vertical flexure and shear zone (Fig. 67). Many ore sections show the following vertical zonation, with two actual examples being illustrated in Figure 68.

Top (6) barren serpentinite
(west)(5) disseminated ore and/or triangular-textured ore } less than 20 weight per cent sulphides
(4) matrix ore, 45 to 65 weight per cent sulphides, sharp contacts with (5)
(3) massive ore as lenses at base of and/or in matrix ore (Fig. 68A)
(2) metasomatic reaction zone, coarse-grained pale amphibole, chlorite and/or biotite; may contain disseminated sulphides, massive ore veins or grade into reaction-zone breccia ore (Fig. 68B)
(1) barren amphibolite, chalcopyrite-rich sulphide veinlets in some areas.

This zonation is seen in reverse in the case of hangingwall ore sections on top of unit 3, but coarse-grained massive ore is a more important component.

Matrix ore is the most abundant component of the orebodies, which accounts for the high average tenor of the deposit. Conspicuous spinel-rich layers do not occur at the base of matrix or massive ore. In general, mineralization that is not on an ultramafic-amphibolite contact is entirely massive ore, which is coarse grained and coarsely layered. An exception to this is seen at the northern end of the basal contact of unit 3 ultramafic, where matrix ore alone continues northwards into the amphibolite. Disseminated, triangular-textured and matrix ores are not foliated, although matrix ore may contain lenses or layers of poorly mineralized serpentinite. Rarely, thin massive sulphide veinlets cut through pegmatite, particularly where the pegmatite has been fractured.

Ore petrology

The deposit is in the oxidized zone to a depth of about 30 m, and supergene sulphides occur to a depth of some 120 m. The bulk composition of the orebodies is more nickel-rich than any other important deposit of the type (Table, 38, Fig. 34). The opaque mineralogy of unoxidized ore is mainly pentlandite-pyrrhotite + chalcopyrite ∓ pyrite ∓ chromite ∓ magnetite. Most chromite is chemically distinct from that commonly present in other nickel sulphide-oxide ores and it may be of metamorphic origin (Barrett and others, 1976). Variations in the mineral proportions of this assemblage and the presence of additional phases are related to the type of ore and the degree to which the ultramafic host rock is retrogressively serpentinized (Hudson, 1973; Barrett and others, 1976). The following descriptions are based on these references.

Where the ultramafic host is little serpentinized, matrix ore consists of pentlandite (50 to 60 per cent of opaque minerals), hexagonal pyrrhotite (20 to 30 per cent), and pyrite (up to 20 per cent) with minor chromite and chalcopyrite. In serpentinized matrix ore pentlandite is partly altered to nickeliferous mackinawite ($Fe_{0.95}Ni_{0.08}S$) and magnetite, chromite is replaced by valleriite, and hexagonal pyrrhotite is rimmed by monoclinic pyrrhotite. Matrix ore is medium grained and generally unfoliated; the sulphides are polygonal and pyrrhotite is mainly strain-free.

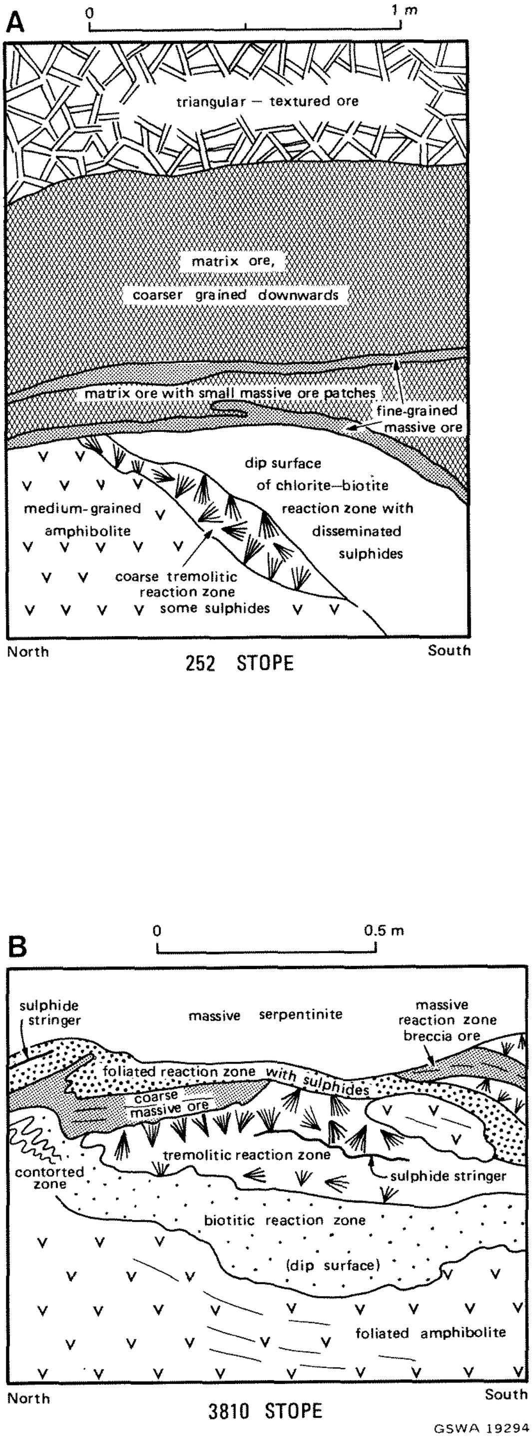


Figure 68. Sketches of mainly vertical underground faces of ore sections in the 2 orebody (A) and the 3 orebody (B), Nepean deposit.

The nickel tenor of matrix ore varies from about 5 to 17 per cent according to the sulphide content, but hangingwall matrix ore seems to have more variable Fe:Ni and Ni:Cu ratios. Reaction-zone ore resembles unserpentinized matrix ore mineralogically, though it appears to be more copper-rich and may contain minor gersdorffite and niccolite. Triangular-textured ore contains pentlandite with subordinate pyrrhotite and chalcopyrite, minor magnetite, but only rare chromite and pyrite. Secondary mackinawite and valleriite are common. Four samples analyzed by Barrett and others (1976) contained between 1.2 and 3.0 per cent nickel and are notably enriched in copper (Table 38). Disseminated ore contains the sulphide assemblages (i) cobaltiferous pentlandite ∓ millerite; and (ii) millerite-heazlewoodite ∓ awaruite accompanied by magnetite and ilmenite.

Massive ores are made up of lenticular layers (up to 2 cm thick) of coarse-grained, fractured pentlandite and lesser hexagonal pyrrhotite which contains many deformation twins and kink bands and is elongated parallel to the layering. Some pyrrhotite is fine grained and forms annealed aggregates of polygonal grains. Pyrrhotite and chalcopyrite fill the fractures and tension gashes in pentlandite. Pyrite, sphalerite and cubanite are rare phases and minor chromite is present. The nickel content of massive ore averages 18 per cent but is very variable as a result of varied Fe:Ni ratios rather than changes in sulphide content. Segregation of chalcopyrite onto the margins of massive ore and into stringers in wallrocks probably accounts for the high Ni:Cu ratio of massive ore (Table 38).

The compositions of the sulphide fractions of the various ore types are similar, with the notable exception of copper (Table 38, column B). The mean nickel content of 20 per cent (in 100 per cent sulphide) sets the deposit apart from many others (Fig. 34). The precious metal content of the ore is also high and agrees with a general positive correlation between nickel tenor and platinum plus palladium content found at Kambalda (Ross and Keays, 1979).

Several features of the deposit, including the widespread presence of reaction zones in the ore section, the presence of triangular-textured ore and of nickel-rich phases in disseminated sulphides, the variable Fe:Ni ratios of massive ore, and the distribution and nature of most chromites, indicate that the high-grade regional metamorphism and subsequent retrograde effects have greatly modified original magmatic features (Barrett and others, 1976; 1977). This is discussed more fully at the beginning of this Chapter and in Chapter 2.

MIRIAM DEPOSIT (31°03′20″; 121°05′40″E)

The Miriam deposit is 13 km south-south-west of Coolgardie, and is the northernmost of three small deposits situated on the eastern contact of a north-striking ultramafic formation (Fig. 65). The deposit has been described by Hallberg and others (1973) and Gemuts (1975), exploration having been undertaken by Anaconda in joint venture with CRA. The poorly exposed ultramafic rock is weathered, silicified, or ferruginized in outcrop. Metabasalt with pillowed textures (indicating facing is westwards) forms low terrain to the east. Following magnetic and induced polarization surveys, percussion drilling of the ultramafic-metabasalt contact in mid-1969 resulted in the discovery of supergene, partly massive sulphides, which over 9.6 m averaged 5.57 per cent nickel and 0.21 per cent copper (drillhole HH 92). Subsequently 18 diamond drillholes tested the steeply dipping contact at varying depths over a strike length of 580 m, and seven of these drillholes encountered mineralization in a strike length of about 150 m. An inferred resource of about 227 000 t averaging 1.7 per cent nickel (3 859 t contained nickel) to a vertical depth of 150 m was estimated by Anaconda following resurveying of the diamond drillholes in 1977.

The ultramafic-metabasalt contact dips at 70 to 80 degrees eastwards near the surface, but it becomes vertical

TABLE 38. AVERAGE CHEMISTRY OF NICKEL ORES AT NEPEAN DEPOSIT

Weight per cent or ppb*	Composite sample of mined ore[a] A	Composite sample of mined ore[a] B	Matrix ore zone[b] B	Matrix ore[c] A	Matrix ore[c] B	Triangular-textured ore[c] A	Triangular-textured ore[c] B	Massive ore[c] A	Massive ore[c] B	Reaction-zone ore[c] A	Reaction-zone ore[c] B
Ni	3.66	*20.1*	*22.4*	11.5	*21.4*	2.0	*17.0*	18.2	*20.0*	11.6	*24.1*
Cu	0.23	1.28	0.7	0.20	0.4	0.7	6.0	0.2	0.2	1.1	2.3
Co	0.06	0.34	0.3	0.16	0.3	0.04	0.3	0.3	0.3	0.17	0.4
Fe	7.60	41.8	39.9	22.0	40.9	4.9	41.4	38.5	42.3	17.7	36.7
S	6.64	36.5	36.6	19.9	37.0	4.2	35.6	33.4	36.7	17.7	36.7
Pt*	315	1824									
Pd*	499	2890									
Au*	293	1697									
Total	Pt + Pd + Au	6411									
Ni:Cu	15.7		32	57		2.8		95		10.5	
Ni:Co	60		75	72		57		67		60	
S:Ni	1.8		1.6	1.7		2.1		1.8		1.5	
Fe:Ni	2.1		1.8	1.9		2.4		2.1		1.5	

Notes:

1. Column A shows mean values of the sulphide fraction of ore.
2. Column B represents data in column A recalculated to 100 per cent sulphides.
3. Sources of data are: a Ross and Keays (1979); b Hudson (1973); c Barrett and others (1976).

or dips steeply west at depth. The contact is marked by a fine-grained chlorite + magnetite ∓ pyrite ∓ pyrrhotite metasedimentary rock generally less than 1 m thick. The ultramafic formation is about 200 m thick and is composed mainly of thin (5 to 15 m) picritic flow units, which may be separated by thin sulphidic metasedimentary horizons. These units are represented by spinifex and granular-textured tremolite-chlorite rocks, which may contain relatively iron-rich porphyroblasts of metamorphic olivine (Hallberg and others, 1973). An apparently conformable lens of partly serpentinized peridotite which is the host to mineralization occurs at the base of the ultramafic formation. This lens is up to about 40 m thick and may terminate at a vertical depth of about 350 m. Massive or weakly foliated, grey or green, mottled and rarely bladed-textured rocks make up the bulk of the lens and consist of partly serpentinized forsteritic metamorphic olivine, accompanied by variable amounts of chlorite, tremolite, talc, carbonate, magnetite and chromite (Hallberg and others, 1973). Tremolite-rich rocks with a static metamorphic texture may occur at the top, but form a better developed zone (up to a few metres thick) at the base of the lens.

Disseminated and lesser massive nickel sulphides are present in a zone 1 to 10 m wide, sub-parallel to and within 3 to 12 m of the ultramafic-metabasalt contact. With increasing depth the mineralized zone narrows and approaches this contact (e.g. as in drillhole MD 3B). Massive sulphides form crudely layered veins (generally up to a few tens of centimetres thick) which are parallel to, or cross-cut, barren ultramafic rock or disseminated sulphides. The disseminated sulphides are fine grained and may occur as weakly developed triangular-textured sulphides (e.g. drillhole MD 2A, 618 to 627 feet). The primary sulphide assemblage probably consisted of pentlandite and pyrrhotite with minor chalcopyrite and pyrite, but is now more or less replaced by supergene violarite, pyrite and marcasite to a depth of 300 m. Minor amounts of niccolite, bravoite and mackinawite are present. The mineralization is completely oxidized to a depth of 50 m. The sulphide mineralization has a high tenor which, in terms of 100 per cent sulphides in drillhole MD 3A, is 16.6 per cent nickel for disseminated sulphides and 23.0 per cent nickel for massive sulphides (Hallberg and others, 1973). The actual nickel assays for these samples are between 0.66 and 4.72, and between 5.22 and 14.20 per cent nickel for disseminated and massive sulphides respectively. Pyrite and millerite occur in the ultramafic rock outside the mineralized zone.

BOUCHERS PROSPECT (31°04′30″S; 121°05′10″E)

This prospect occurs 3.5 km along strike to the south-southwest of Miriam deposit in the same stratigraphic position (Fig. 65). Whilst prospecting the area for beryl in 1959, H. Boucher found traces of nickel. Subsequent exploration has been carried out from 1966 to 1971 sequentially by Anaconda, Conwest, Metals Ex. and MCE under option agreements.

Limited diamond drilling of the ultramafic-mafic contact by Conwest in 1968 encountered up to 10 per cent disseminated nickel sulphides in serpentinite or tremolitic ultramafic rock. In late 1970 MCE excavated 35 costeans to expose the contact between ultramafic rocks to the west and metagabbro to the east. Geochemical chip sampling of the ultramafic-metagabbro contact outlined two anomalous areas, in a strike length of some 1 000 m, in which metasediment is partly absent from the contact. In early 1971, 21 diamond drillholes (total 4 355 m) were bored by MCE to test the surface geochemical anomalies. Nine of these drillholes intersected mineralization assaying between 0.50 and 3.46 per cent nickel (average Ni:Cu = 30) over drilled widths of from 0.3 to 2.1 m at vertical depths between 77 and 186 m. Massive sulphides assaying 7.83 and 9.74 per cent nickel each over 0.41 m widths, were encountered in two drillholes. The bulk of the mineralization occurs within a strike length of 380 m. The deeper intersections contain pentlandite and pyrrhotite plus chalcopyrite, but supergene violarite and pyrite prevail in most drillholes.

Two deeper diamond drillholes designed to test the contact at depth (300 to 400 m), were suspended before the contact was intersected.

NORTH BOUCHERS PROSPECT
(31°03′50″S; 121°05′30″E)

North Bouchers prospect occurs on the prospective Miriam-Bouchers ultramafic-mafic contact, some 1 200 m south of Miriam deposit (Fig. 65). No further details were available at the time of writing, but the prospect appears to be a similar but smaller version of the Bouchers prospect.

REMAINING DEPOSITS IN THE KALGOORLIE-NORSEMAN REGION

SCOTIA DEPOSIT (30°12′05″S; 121°16′40″E)

Introduction

The Scotia deposit is 63 km north-northwest of Kalgoorlie near the eastern margin of an elongate strip of supracrustal rocks (Plate 1). A small gossanous outcrop (1.1 per cent nickel assay) was found by J. Jones in 1967, and shallow drillholes into the underlying mineralized zone intersected nickel sulphides in February 1968. Gossan analyzed by Travis and others (1976) contained 1.12 per cent nickel, 0.20 per cent copper, 595 ppb palladium and 781 ppb iridium.

A partnership of Great Boulder (51%) and N. Kalgurli (49%) acquired the mineral claims in May 1968 and undertook diamond drilling, from which an indicated sulphide ore reserve of 1.13 Mt averaging 3.07 per cent nickel (34 691 t contained nickel) and 0.25 per cent copper was estimated. Shaft sinking began in September 1968 and full production of ore commenced on October 13, 1969. Great Boulder converted its disused gold treatment plant at Fimiston to a nickel treatment mill.

The Scotia mine closed on September 8, 1977, at which time officially reported production amounted to 14 628 t of nickel in ores and concentrates. Average head grades were 2.17 per cent nickel and 0.15 per cent copper. Annual production in the first four years of operation exceeded that at Nepean (Table 2), but in mid-1974 the collapse of a floor pillar and later of the hangingwall resulting in a halving of production because mining had to be restricted to below the 253 m level. Development of the mine took place on six levels spaced at depths from 70.1 to 356.6 m below surface, and the main ore shoot has been stoped out between depths of 48 and 320 m. Remaining demonstrated resources to a depth of 340 m (the lower limit of the shoot) are estimated at 149 463 t averaging 1.53 per cent nickel (2 287 t) contained nickel. Great Boulder gained full control of the mine in March 1975 and the same company became a wholly owned subsidiary of WMC in February 1976.

Stratigraphy

The Scotia deposit is situated on the eastern, west-facing limb of a major syncline which extends north-northwest to Menzies, and south towards Kalgoorlie. Granitoid terrain to the east occupies a southeasterly plunging anticline. Felsic volcaniclastic metasedimentary rocks form the core of the syncline and overlie a sequence of mafic to ultramafic rocks, which Williams (1976) correlated with the Kambalda and Coolgardie sequences.

The stratigraphy at Scotia is summarized in Table 39 which draws on data in Barry (1974), Christie (1975) and Nesbitt and Sun (1976). The ultramafic formation is characterized by rocks containing static igneous textures including various types of spinifex and skeletal textures (Nesbitt, 1971), lapilli tuff, flow-top breccia, cumulus, subequant olivine/serpentine, and amygdaloidal textures. The excellent preservation of primary textures and the lack of foliation contrasts with the overlying metasedimentary rocks and the footwall amphibolite. The present mineralogy includes brown, relict igneous olivine (variably altered to antigorite), tremolite-actinolite, chlorite, talc, calcite, dolomite and magnesite.

TABLE 39. STRATIGRAPHY OF THE SCOTIA DEPOSIT

Informal name	Lithology	Approx. thickness (m)
Metasedimentary sequence	Quartz-mica schist	>600
Ultramafic formation	Metamorphosed picritic and peridotitic flow units with thin metasedimentary or magnesian metabasaltic horizons; basal lens-shaped serpentinized olivine peridotite to dunite with nickel mineralization at base	500-600
Footwall metasediment	Quartz-albite-biotite schist (some tuffaceous textures) and pyritic black slate	15
Footwall amphibolite	Tholeiitic and magnesian metabasaltic rocks, foliated	150
Dacitic pyroclastics (metamorphosed)		200
Tonalite (intrusive)		

The basal olivine-rich ultramafic rock which is host to the mineralization, is a lensoid unit about 500 m long, up to 45 m thick and extending to a depth of at least 370 m (Christie, 1975). The unit consists of massive, or weakly foliated, green-grey to black serpentinite containing medium-grained, granular, relict igneous olivine (Fo_{88-93}), and/or antigorite after olivine, and minor to accessory chlorite, talc, magnetite, chromite and carbonate minerals. Schistose talc and carbonate-rich varieties are common at the basal contact. Christie (1975) indicated a magnesia content for the unit of nearly 45 per cent, which is the most magnesian composition known for the host of a volcanic peridotite-associated deposit. It is not evident whether the unit represents a flow, exceptionally rich in olivine phenocrysts, or a shallow intrusive body.

The metasedimentary horizons within the ultramafic formation are foliated, and consist of sulphidic black slate, albite-quartz rocks, and actinolite/tremolite-chlorite-biotite ∓ albite assemblages. The footwall metasediment is variable in composition, being a pale felsic rock, or a green amphibolitic rock which may grade downwards into the footwall amphibolite. Fine-grained quartz, albite, actinolite and biotite are the chief minerals, though some albite is coarse grained and may be of tuffaceous origin. Thin layers of laminated chert or pyritic slate are also present in the footwall metasediment.

The footwall amphibolite consists of variably foliated and/or lineated fine- to medium-grained metabasaltic rocks which Sun and Nesbitt (1978) have subdivided into two groups based on rare earth element abundances. The mineralogy is hornblende or actinolite, plagioclase, quartz and chlorite.

Based on the assemblages in the basal ultramafic unit (relict igneous olivine and antigorite) and the footwall amphibolite (deep-green hornblende - calcic plagioclase), Barrett and others (1977) estimated metamorphic grade to be low amphibolite facies.

General structure

The dip of the layering or foliation is towards the west at between 60 and 80 degrees. Although the strike of the basal contact of the ultramafic rock is generally north-northwest, there are two pronounced embayments where the strike changes to a north or north-northeast orientation (Fig. 69). The northerly embayment is occupied by the olivine-rich ultramafic which is host to the Scotia deposit, and some 750 m to the south is a smaller embayment which also contains an olivine-rich ultramafic rock at shallow depth. Drilling of the southern embayment to a depth of 275 m has failed to detect mineralization of economic interest.

The northerly embayment, the ultramafic host, and the deposit itself all plunge south at about 70 degrees. The deposit is centrally located within the ultramafic host and is at its basal contact. The average strike length of the mineralization is 150 m, and the mean thickness is 20 m. Below a depth of 300 m the embayment, ultramafic unit, and deposit narrow, and though mineralization of economic interest appears to terminate at about 370 m, the ultramafic host persists at a much reduced strike length of some 100 to 150 m (Fig. 70).

Christie (1975) ascribed the formation of the main, ore-bearing embayment to flexural folding. However, the confinement of the ultramafic host to this embayment argues for some degree of control by an original topographic depression in the top of the footwall sequence. A significant feature in this respect is that a foliated to schistose mafic metasedimentary horizon overlying the ultramafic host appears to overstep this unit along strike to the north and south, and thus rests directly in contact with the footwall sequence (Fig. 69). This does not discount the presence of flexural folds which may account for smaller scale irregularities in the dip and strike.

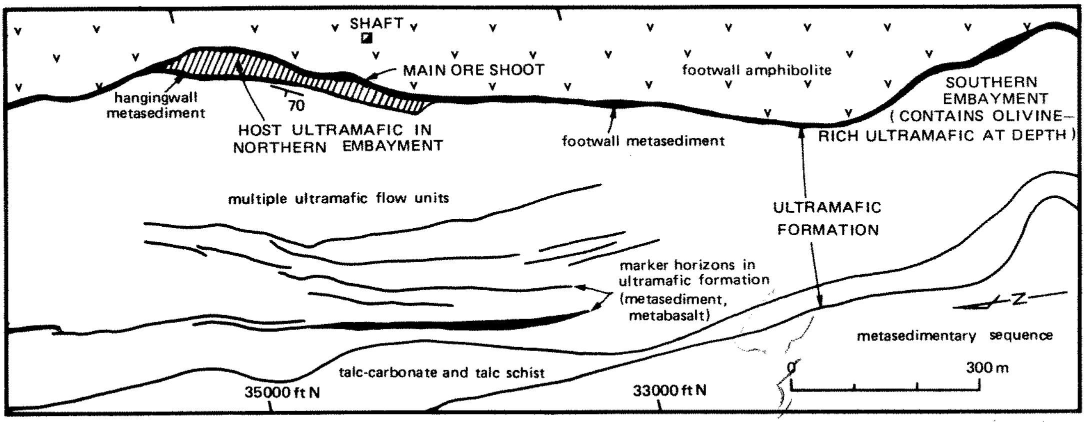


Figure 69. Surface geology of the Scotia deposit (data from Great Boulder Mines Ltd).

Ore distribution and structure

Nickel mineralization is confined to the basal 20 m of the ultramafic host, and consists mainly of disseminated sulphides with a central basal zone (in longitudinal projection) of discontinuous matrix, massive and breccia sulphides up to 2 m thick (Fig. 70). Massive sulphides also occur as veins in the less sulphidic ore types. The footwall contact of the ore section is the locus of shear deformation; chloritic schist developed at the contact may represent a deformed metasomatic reaction zone and the overlying ultramafic rock is commonly a talcose schist. Massive to breccia sulphides are layered or foliated and locally folded, and in detail are irregularly distributed. Tectonic inclusions of the underlying footwall metasediment may occur in the basal ore section.

Ore petrology

The primary opaque minerals are pentlandite and pyrrhotite accompanied by minor pyrite, chalcopyrite (or cupriferous valleriite), magnetite and chromite. Mackinawite may replace pyrite. The pentlandite:pyrrhotite ratio in massive ore is typically about 2.0 resulting in nickel assays of around 15 to 20 per cent. Lenses of fine-to-medium pyrite and pentlandite (comparable to fine pyritic ore of Juan shoot, Kambalda) are present in some massive ore. The proportion of pentlandite increases upwards in disseminated ore as the pentlandite:pyrrhotite ratio changes from about 2.0 to 40 (Christie, 1975). Nickel content of disseminated ore ranges from 1 to 7 per cent, commonly with a sharp cut-off at 0.8 to 1.0 per cent nickel with the overlying serpentinite. The barren part of the ultramafic host contains pentlandite which may be replaced by heazlewoodite and millerite, particularly where serpentinization is complete. The sulphides are fine to medium grained and are statically recrystallized with silicates (serpentine especially). A fine-scale foliation is present in some massive ore and is defined by oriented gangue inclusions and elongate pyrrhotite which contains deformation twins and kink bands. Pentlandite aggregates are lenticular and cracked, and some are veined by magnetite. These textures are less pronounced or absent in disseminated ore, which is typified by polygonal mosaics of little-strained pyrrhotite and coarser grained pentlandite. Blebby sulphide aggregates occur in some sulphide-rich disseminated ore. Pentlandite and pyrite are the chief sulphide minerals in some samples of disseminated ore.

The bulk composition of Scotia ore as determined by assay of concentrates is given in Table 40. In terms of the Fe-Ni-S system this composition plots close to Nepean but on the sulphur-rich side of the mss field because of the greater pyrite content of Scotia ore compared with Nepean ore (Fig. 34).

TABLE 40. BULK COMPOSITION OF SCOTIA DEPOSIT

Weight per cent or ppb*	Recalculated to 100% sulphides
Ni	23.1
Cu	1.45
Co	0.36
Fe	39.4
S	35.7
Pt*	1 461
Pd*	3 110
Au*	1 020
Total Pt + Pd + Au	5 591
Ni:Cu	15.9
Ni:Co	63
S :Ni	1.5
Fe:Ni	1.7

Note:
Based on a sample of 3 206 t of concentrates with recalculation to 100 per cent sulphides based on analysis of the silicate fraction (data are from Ross and Keays, 1979).

The deposit is oxidized to a depth of 43 m and supergene violarite extends to a depth of at least 200 m in the sulphide-rich ores.

RINGLOCK PROSPECT (30°07′55″S; 121°26′50″E)

Ringlock prospect is some 18 km northeast of the Scotia deposit and 6 km northwest of Ringlock Dam. The prospect, which is separated from the Scotia deposit by an anticlinal area of granitoid rocks which strikes north-northwest, occurs at the northern end of a narrow (ca. 600 m wide) zone of northwest-striking mafic to ultramafic rocks. Lenticular ultramafic units within the zone can be traced over a distance of some 20 km from near Rainbow Dam in the south to Ringlock prospect in the north. Granitoid rocks occur to the east of the zone, but, except at the northern end, felsic metasedimentary or metavolcanic rocks, bordered westwards by another narrow strip of mafic to ultramafic rocks (Mount Jewell), are interposed between the zone and the main anticlinal area of granitoids to the west. Granitoid dykes are common in the north. Dips are vertical or steeply to the west or east. The area is covered in soil or laterite, and bedrock information is derived from

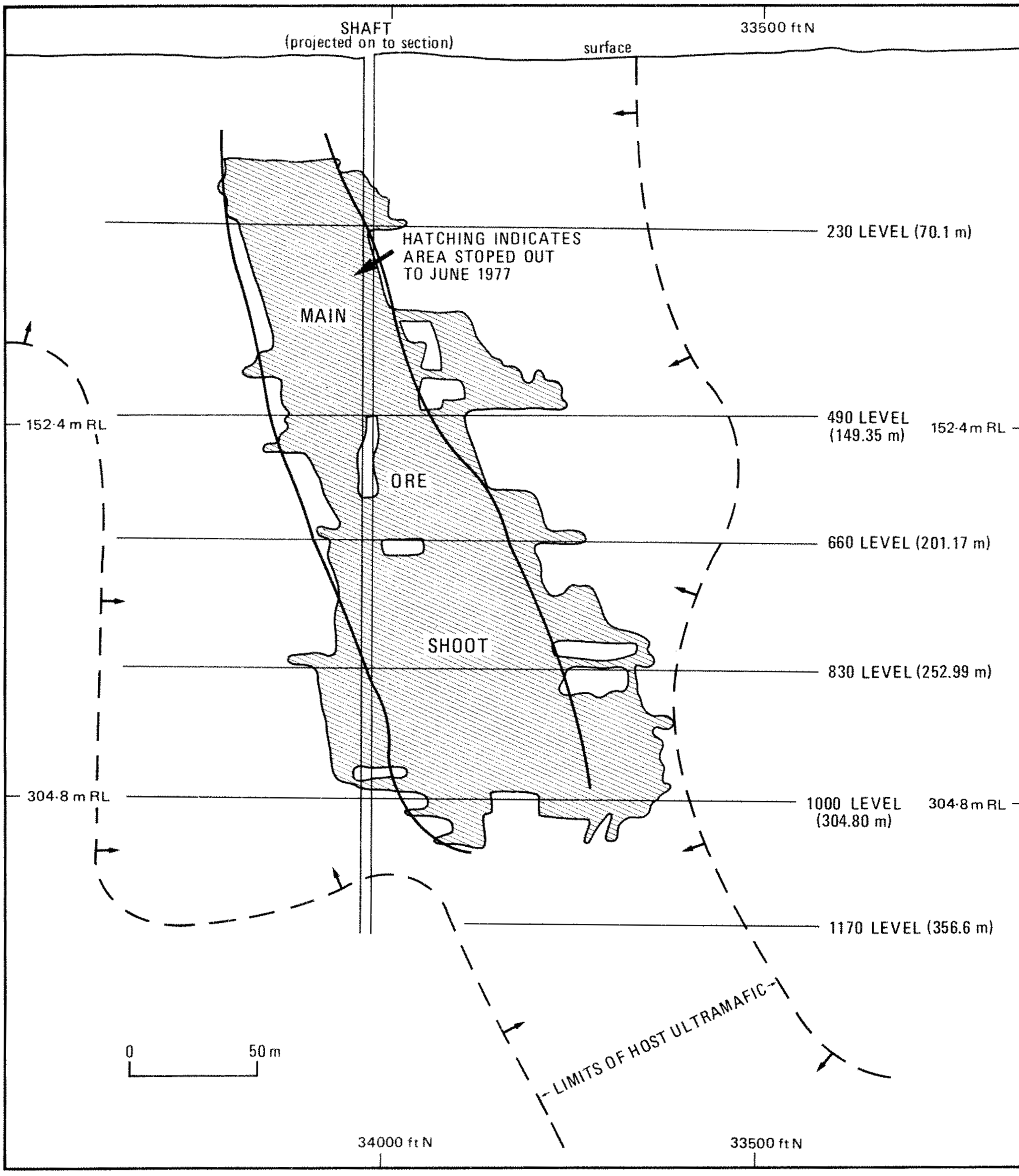


Figure 70. Vertical longitudinal section projection (looking east) of the Scotia deposit.

magnetic surveys and drilling programmes. The ultramafic rocks may be deeply weathered to more than 100 m below surface.

Exploration activity in the mafic-ultramafic zone described was initially concentrated in the south at East Scotia prospect, which is near Ringlock Dam. The zone was regarded as a probable equivalent of the ultramafic formation at Scotia. The discovery of nickel sulphides at East Scotia in late 1970 stimulated exploration further north which was conducted mainly by Kennco, Unimin and Cominco-Abminco in the period 1971 to 1977. The most detailed and systematic exploration was undertaken by WMC (Travis and others, 1976a) in the area from East Scotia to the southern boundary of Ringlock prospect in the period 1974 to 1977. Travis and others' (1976a) interpretation of the stratigraphy of the mafic-ultramafic zone is summarized in Table 41. Most rocks are foliated, except the olivine-rich ultramafic units. Important nickel mineralization is restricted to the western contact of the central ultramafic sequence. This contact is interpreted to be the basal contact of the sequence, as deduced from trends towards a decline in magnesia content eastwards and from spinifex textures. The footwall metadolerite is largely removed by granitoid intrusions in the Ringlock prospect area.

TABLE 41. STRATIGRAPHY OF THE RINGLOCK —EAST SCOTIA AREA

Informal name	Lithology	Approx thickness (m)
(6) Un-named (east)	Tholeiitic metabasalt	200
(5) Upper ultramafic sequence	Serpentinite, talc-carbonate, talc-chlorite; amphibole-chlorite; mainly extrusive; less magnesian eastwards (presumed facing direction)	300
(4) Un-named	Magnesian metabasalt, meta-dolerite and minor amphibole-chlorite and metasediment	<50
	Sulphidic black slate-chert-felsic to ultramafic tuff marker horizon	<10
(3) Central ultramafic sequence	Upper extrusives: talc-chlorite, amphibole-chlorite with spinifex and brecciated flow tops, metabasalt; less magnesian eastwards	30-120
	Lower dunitic intrusive: granular, medium- to coarse-grained serpentinite, talc-carbonate, some relict olivine, less magnesian on margins; mineralized	150
(2) Footwall metadolerite	Fine- to medium-grained, may be silicified at top	200
(1) Lower ultramafic sequence (west)	Dunite altered to serpentinite or talc-carbonate; occurs locally within (2); minor mineralization	20

Data are from Travis and others (1976a).

Percussion and diamond drilling undertaken by Kennco and Unimin in 1972-1973 encountered low-grade disseminated nickel sulphides at or near the basal contact of the central ultramafic sequence over about 1 000 m of strike at the southern end of Ringlock prospect. The best diamond drillcore intersections were of 0.7 to 1.0 per cent nickel as disseminations in serpentinite over widths of between 1 and 3 m. Drilling by Cominco-Abminco (18 diamond drillholes) encountered some sporadic, mainly disseminated, mineralization in the contact zone for a further 2 500 m north of the Kennco-Unimim area, but continuity of mineralization was indicated in only one area some 200 m in strike length. Typical intersections in diamond drillcore from serpentinite assayed 0.7 to 1.2 per cent nickel over widths of between 1.8 and 10 m, with Ni:Cu ratios being in the range 9.6 to 24. Higher grade intersections of 3.1 to 3.3 per cent nickel over 0.5 m were recorded from veins offset into foliated siliceous rocks (metasediment or deformed granitoid) and porphyry intrusions. Most mineralization is fine grained and at least partly oxidized. The opaque minerals are pentlandite altering to violarite, secondary pyrite after pyrrhotite, and chalcopyrite, plus accessory magnetite, chromite altering to valleriite and marcasite.

The grade and width of mineralization appear too low to warrant further infill drilling along strike or deeper drilling at the main prospect.

EAST SCOTIA DEPOSIT (31°11′10″S; 121°27′20″E)

The regional geology of this prospect has been described under the Ringlock prospect. East Scotia prospect is 1.5 km southwest of Ringlock Dam, 6 km southeast of Ringlock prospect and is 1 km south of where the Scotia - Carr Boyd road crosses the mafic-ultramafic zone containing both prospects. Outcrop is rare because of extensive laterite and colluvium or alluvium.

Exploration before 1973 was mainly conducted by a consortium of Group Explorations (50 per cent), Sumitomo (25 per cent) and Nomura Trading Company (25 per cent), known as G & S Explorations Pty Ltd, and from 1974 to 1977 by WMC in joint venture with this consortium. Between mid-1970 and mid-1972 G & S Explorations completed 135 percussion drillholes (9 520 m) and 46 diamond drillholes (9 889 m) covering about 8 km of strike between Ringlock prospect and a point 3 km south of East Scotia prospect. This drilling included testing of targets (mainly based on induced polarization anomalies) in all three ultramafic sequences (Table 41), but with the intersection of nickel sulphides in three percussion drillholes penetrating the base of the central ultramafic sequence in November 1970, intensive effort was concentrated on the prospect itself. In 1975 WMC completed two diamond drillholes (286 m) to test for extensions of the mineralized zone. Excluding an isolated deep intersection (drillhole GS 44), Travis and others (1976a) estimated nickel sulphide resources at 83 900 t averaging 2 per cent nickel (1 678 t contained nickel) using a 1 per cent cut-off figure and a minimum width of 1.52 m. Exploration by WMC, which included a detailed aeromagnetic survey, geochemical drilling (1 730 m) and relogging of the earlier drilling, has resulted in a better appreciation of bedrock geology and stratigraphy (Table 41). Dips are vertical or steeply to the west or east.

The main concentration of mineralization at East Scotia is at the base of the central ultramafic sequence, at the southern end of a lens of metadunite some 1 500 m long, and up to 180 m wide (Travis and others, 1976a). The host rock is a medium-grained, cumulus-textured serpentinized peridotite to dunite which is sporadically converted to a talc-magnesite/dolomite ∓ chlorite ∓ amphibole rock at its margins and where it is intruded by foliated felsic dykes. Mineralization is in the less magnesian basal (western) margin of the meta-dunite, in the form of fine-grained disseminations and irregular veins or lenses of breccia sulphides in foliated talc-chlorite-dolomite and amphibole-chlorite rocks. Mineralization occurs along the basal contact over a strike length of 300 m, but is only well developed in a small shoot some 50 m long which plunges at 75 degrees towards the southeast and has a vertical extent from 45 to 175 m below surface. Typical intersections in this shoot contain an average of between 1.2 and 2.5 per cent nickel over a true width of 1.7 m. Isolated veins and patches of higher grade mineralization occur 3 to 6 m above the basal contact in two drillholes. Sulphide assemblages are dominated by supergene pyrite and violarite after primary pyrrhotite-pentlandite-pyrite. Oxidation is complete to a depth of about 45 m.

BARDOC PROSPECT (30°19′05″S; 121°17′10″E)

Bardoc prospect is 670 m southwest of Mount Vetters homestead which is situated on the Kalgoorlie-Menzies road, 48 km north-northwest of Kalgoorlie. The regional setting of the prospect represents a southern extension of the stratigraphy at Scotia deposit (Table 40), with the difference that the ultramafic formation (here only about

50 m thick) is succeeded westwards by a thin formation of tholeiitic metabasalt to metagabbro intercalated with the base of the metasedimentary sequence. The dip is steep towards the west. Disseminated sulphides and rare lenses of matrix sulphides occur in a fine-grained, foliated actinolite + chlorite rock present at the top (western) contact of the ultramafic formation (Shackleton, 1972). Monoclinic pyrrhotite is the dominant sulphide and is accompanied by violarite after pyrrhotite, chalcopyrite and smythite. Amax carried out exploration in the area in the period 1967 to 1973. The best intersections encountered in diamond drillholes contained between 0.5 and 0.9 per cent nickel over widths up to 2 m in a strike length of some 450 m.

The affinities of the mineralization in the context of volcanic peridotite-associated deposits are not clear. The host rock appears to be of volcanic origin and could represent the A zone of an ultramafic flow. The apparent absence of primary nickel sulphide is a discouraging economic factor.

DUPLEX HILL AREA PROSPECTS

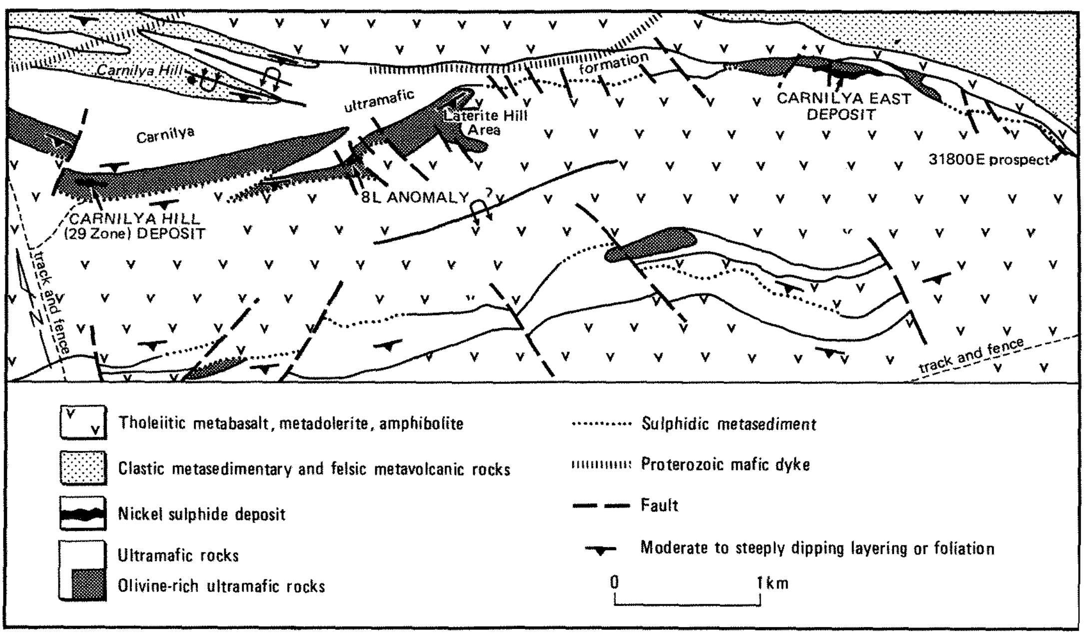
The Duplex Hill area is some 35 km southeast of Kalgoorlie, and about 5 km south of the Kalgoorlie - Mount Monger road. Mafic to ultramafic rocks and clastic metasedimentary rocks strike between northeast and northwest, and generally dip westwards at moderate to steep angles. In regional setting the area lies between two anticlinal zones: the Kalgoorlie-Kambalda zone to the west and the Bulong - Mount Monger zone to the east. Williams (1976) interpreted the Duplex Hill mafic to ultramafic sequence as being younger than the Kalgoorlie-Kambalda sequence although in earlier mapping he correlated the two sequences (Williams, 1970). Interpretation is hampered by poor outcrop and probable complex structure: cherty metasedimentary horizons on contacts between mafic and ultramafic formations indicate the presence of plunging folds, and facing determined from spinifex textures and sedimentary structures suggests some overturning of the stratigraphy.

Exploration for nickel along basal ultramafic contacts has been carried out sporadically during the period 1968 to 1974 by Conwest, Amax and Anglo American, in that order. Most work was done by Amax who undertook geological, ground magnetic, induced polarization and soil geochemical surveys, followed by 15 125 m of non-core drilling and 433 m (4 drillholes) of diamond drilling. Many targets appear to have been related to sulphidic metasedimentary horizons along ultramafic contacts. The diamond drilling took place at three prospects informally named here the Duplex Hill, Duplex West, and Walkers Find prospects. These are located 5 km east, 1.5 km south-southeast and 4 km north, respectively of Penglaze Dam.

Duplex Hill prospect (30°57′20″S; 121°45′20″E) is immediately south-southwest of Duplex Hill itself. The strike is north-northeast and the dip is steeply to the west. An ultramafic formation consisting mainly of metapicritic and metabasaltic flow rocks appears to face eastwards and is in contact with amphibolite and metadolerite to the west. Olivine-rich ultramafic rocks seem to be lacking. A cherty metasediment occurs along the contact. Three diamond drillholes (two drilled by Conwest) sunk into the contact zone along an 800 m strike length encountered fine stringers and disseminations of sulphides in the foliation of a brecciated tremolite-chlorite + talc + carbonate rock. The best intersection was in DHD 1 (Amax) which averaged 0.95 per cent nickel and 0.02 per cent copper over 0.3 m. The sulphides consist of pyrrhotite, pyrite, pentlandite/violarite and chalcopyrite.

At Duplex West prospect (30°57′50″S; 121°42′50″E) the strike is north-northwest and the dip steeply to the west. The presumed basal contact of an ultramafic formation is again marked by cherty metasediment, but the mineralization occurs in carbonated and serpentinized peridotite. Two diamond drillholes put down by Amax were spaced 120 m apart along strike and intersected disseminated pyrrhotite, pentlandite and chalcopyrite; the best intersection was 7.9 m averaging 0.64 per cent nickel and 0.07 per cent copper in drillhole DHD 3.

The Walkers Find prospect (30°55′15″S; 121°43′15″E) is 2 km west-southwest of the abandoned gold workings of that name. A contact between mafic metavolcanic rocks and serpentinite or talc-carbonate dips steeply west and plunges south. Amphibole-chlorite rocks and cherty metasediments occur in the contact zone and



GSWA 19297

Figure 71. Geological setting of the Carnilya Hill and Carnilya East deposits (data from BHP and WMC).

one diamond drillhole encountered disseminated sulphides, including a vein (15 cm thick) of massive sulphide, in amphibole-chlorite. The average assay over a true width of nearly 1 m was 1.14 per cent nickel. Violarite, pyrite and chalcopyrite are the sulphide minerals.

Further evaluation seems warranted to determine the possible presence of olivine-rich ultramafic rocks, particularly where metasediment is absent from the basal contact.

CARNILYA HILL DEPOSIT
(31°02′50″S; 121°48′30″E)

Carnilya Hill of '29 zone' deposit is 58 km southeast of Kalgoorlie in a belt of east-southeasterly striking mafic to ultramafic rocks (Fig. 71). Traced westwards the strike changes to the north in the Mount Martin area and northward continuity with the Duplex Hill area is indicated (Plate 1). Williams (1976) interpreted the Carnilya Hill mafic to ultramafic sequence as being younger than the Kalgoorlie-Kambalda sequence, apparently because the belt is regarded as synclinal. Heath and Arndt (1976) pointed out that though an inclined syncline-anticline couple is present at Carnilya Hill itself (Fig. 71), in regional terms the sequence appears to be on the south-dipping limb of a broad south-southeasterly plunging anticline known as the Bulong anticline. The dip is consistently southwards, therefore the inclined folds may simply be repeating the stratigraphy of an anticlinal limb which, overall, becomes younger to the south. Further work is needed to resolve this satisfactorily.

The ultramafic rocks at Carnilya Hill deposit dip south-southwest at 45 to 50 degrees, but the presence of spinifex textures and a systematic decrease in the magnesia content indicate that the ultramafic formation faces northwards and is therefore overturned (Heath and Arndt, 1976). The metamorphosed olivine-rich ultramafic rocks appear to be thickest in the vicinity of the deposit. The stratigraphy is summarized in Table 42. Thin cherty or carbonaceous sulphidic metasedimentary horizons occur throughout the Carnilya ultramafic formation which is interpreted as a flow sequence. Faults which cut the basal part of the formation do not displace the upper contact (Fig. 71). Igneous textures are preserved in many of the mafic and ultramafic rocks. Regional metamorphic grade appears to be low amphibolite facies with both static and dynamic textures developed. Outcrop is good over the ultramafic rock but poor over the footwall mafic formation.

TABLE 42. STRATIGRAPHY OF THE CARNILYA HILL AREA

Informal name	Lithology	Approx thickness (m)
(3) Upper metasedimentary formation (north)	Black slate, phyllite, recrystallized chert and banded iron-formation, quartz-sericite or chlorite schist, felsic metavolcanic rocks	150
(2) Carnilya ultramafic formation	Upper: mainly tremolite/actinolite-chlorite and hornblende-chlorite-plagioclase rocks of picritic to basaltic composition	450 (max)
	Lower: mainly antigorite serpentinite or talc-magnesite/dolomite + serpentine + chlorite and tremolite-chlorite / ∓ talc ∓ serpentine of peridotite to olivine peridotite composition; nickel sulphides at base of third flow up from base of formation	180 (max)
(1) Footwall mafic formation (south)	Basic to intermediate metavolcanics represented by dark-green hornblende-calcic plagioclase-quartz and plagioclase-hornblende-biotite-quartz rocks; massive or foliated	>350

Exploration of the area of the deposit was carried out from 1966 to 1973 by BHP (as managers) in equal partnership with INAL. The following account is largely drawn from a summary report by Heath and Arndt (1976). In 1967 the drill testing began of anomalies detected by soil sampling or induced polarization surveys. Most targets proved to be sulphidic or carbonaceous metasedimentary horizons but gossan was found in one coincident nickel-copper geochemical anomaly. Diamond drillhole DDH 29 was designed to test an induced polarization anomaly below the gossan, and nickel sulphides where intersected at 95 m drilled depth in November 1968. Later sampling showed that variably silicified discontinuous lenses of gossan found over a 430 m strike length averaged 0.54 per cent nickel and 0.19 per cent copper. By mid-1973 some 105 percussion drillholes (7 781 m) and 30 diamond drillholes (4 725 m) had been completed. Demonstrated sulphide resources were estimated at 42 300 t averaging 5.6 per cent nickel (2 369 t contained nickel) and 0.7 per cent copper, using a 1 per cent cut-off figure and with no allowance for dilution. Oxidation is complete down to 16 to 35 m depth, but supergene sulphides are not well developed below.

Nickel mineralization is concentrated at the base of the third flow unit which is about 65 m stratigraphically above the base of the formation. This unit consists of 21 m of talc-magnesite serpentinite (some cumulus-textured) B zone material averaging about 36 per cent magnesia, overlain by about 2 m of spinifex-textured serpentine-chlorite-tremolite rock representing the A zone of the flow. The mineralization consists of small lenses of massive and matrix sulphides, generally 1 to 2 m thick, which are spread over a strike of 450 m but persist only to a vertical depth of 150 m. Two mineralized horizons separated by 7 m of ultramafic occur at the west end of the shoot. Barren iron sulphides (metasedimentary horizon?) occur downdip of the shoot.

The primary opaque mineralogy is pyrrhotite and lesser pentlandite with minor chalcopyrite, pyrite, chromite, magnetite and ilmenite, and rare niccolite, gersdorffite and bravoite. The pyrrhotite:pentlandite ratio averages 2.3 resulting in an average assay for massive sulphides of 10 per cent nickel. Traces of sphalerite, galena and telluride minerals are associated with chalcopyrite-rich veins. Massive sulphide is stratigraphically overlain by thicker matrix-to-disseminated sulphide. Mineralogical layering is absent or poorly developed in massive sulphide but a fine-scale foliation defined by oriented antigorite may be present. Pyrrhotite may contain deformation twins and kink bands or be annealed into polygonal aggregates of little-strained grains. Chromite and magnetite may form a thin layer at the stratigraphic base of massive ore, and may also be concentrated at the massive-matrix sulphide boundary in a like manner to Kambalda ores. Deformation is less evident in matrix and disseminated sulphide: the sulphides occur between antigorite pseudomorphs after sub-equant olivine, though some antigorite is bladed and shows a static metamorphic intergrowth texture with sulphide.

Carnilya Hill deposit seems comparable to the hangingwall ores of Kambalda in style and setting, but not in terms of size.

CARNILYA EAST DEPOSIT
(31°03′20″S; 121°51′20″E)

Carnilya East deposit is 5.5 km east of and along strike from the Carnilya Hill deposit (Fig. 71). The Carnilya ultramafic formation is much thinner here, though it is not clear to what extent this is due to stratigraphic versus tectonic thinning. The northern contact of the ultramafic formation is notably uncomplicated compared with the southern contact until it becomes involved in the Carnilya Hill folds (Fig. 71). The apparent discordance north of Carnilya Hill also suggests that a strike fault could extend eastwards to form the northern contact of the ultramafic formation. Strong deformation and metasomatism are certainly a characteristic of the attenuated ultramafic formation and associated mafic rocks at Carnilya East and eastwards from there.

In February 1973, W.D.M. Hall found a very siliceous gossan whilst engaged in geological mapping for BHP. The average assay of 13 samples was 0.30 per cent nickel and

0.09 per cent copper. A discontinuous gossan some 270 m long was outlined with the aid of costeans, and in December 1974 a percussion drillhole (PB 571), sited to test the gossan below the water table, intersected massive nickel sulphides which assayed 5.95 per cent nickel over 2 m drilled width. Six percussion drillholes (610 m) and four diamond drillholes (547 m) were then drilled. Massive sulphides were encountered in two diamond drillholes, the best assay being 5.96 per cent nickel over a true width of 1.43 m. In December 1976, WMC commenced detailed exploration in the area in joint venture with BHP. The holding is currently WMC with 56 per cent and BHP with 44 per cent. During 1977, 115 percussion drillholes (4 169 m) and 8 diamond drillholes (1 265 m) were drilled to further investigate the deposit itself, and to delineate and test the attenuated ultramafic formation to the east, where outcrop is largely absent. Recently published (June, 1981) ore reserves of this deposit are 500 000 t of ore averaging 4.2 per cent nickel (21 000 t contained nickel), with one third of this reserve being supergene pyrite-violarite and the remainder being transition zone sulphides.

The southern, and presumed basal stratigraphic, contact of the ultramafic formation dips south at between 40 and 75 degrees, and the formation is 40 to 80 m thick. Foliated fine-grained tholeiitic metabasalt is in contact with the ultramafic formation to the north and south. The southern, and mineralized, contact zone is characterized by the presence of vein quartz and massive or foliated hybrid rocks containing quartz, feldspar, chlorite, tremolite rosettes, and small carbonate porphyroblasts. The metabasalt is commonly silicified and variably affected by biotite, tremolite and carbonate alteration within 10 m or so of the contact, or in association with off-contact mineralization (Fig. 72). The hybrid rocks may represent a metasomatic reaction zone developed during regional metamorphism at the metabasalt-ultramafic contact, which has been subject to further metasomatism associated with hydrothermal silicification. The ultramafic formation is dominantly foliated talc-magnesite/dolomite ∓ chlorite, but at the eastern end of the deposit there is a large lens of amphibole-chlorite ∓ feldspar rocks derived from basaltic to picritic flows, as intersected in drillhole CHD 8 (Fig. 72). Cherty of carbonaceous metasedimentary horizons, some containing iron sulphides, occur in the amphibole-chlorite rocks and the tholeiitic metabasalt, and on the contacts of the ultramafic formation but appear to be absent from the talc-carbonate rocks.

Nickel sulphides occur in the southern contact zone over a strike length of 420 m and to a vertical depth of about 160 m where the deposit may be terminated by a north-dipping reverse fault. The deposit is oxidized to a depth of 40 to 70 m. Much of the mineralization is present as disseminations, blebs and stringers, and thick veins or lenses of breccia ore in metasomatized tholeiitic metabasalt or hybrid rock (e.g. Fig. 72). The breccia ore contains inclusions of metabasalt and boudinaged quartz or carbonate veins in fine- to medium-grained sulphides, which are well foliated, and, in some places, mineralogically layered. The primary sulphide assemblage is pentlandite and pyrrhotite with minor pyrite and chalcopyrite. The average tenor of massive sulphide is about 10 per cent nickel indicating a pyrrhotite-pentlandite ratio of 2.3. The mean Ni:Cu ratio is about 20 to 24. Sulphide textures are similar to those described from Carnilya Hill. Pyrrhotite textures vary from strongly deformed to annealed in massive sulphides. Deformation is less evident in less sulphidic ores and static recrystallization with silicates is developed. Static textures superimposed on earlier dynamic metamorphic textures are also a feature of the silicates in tholeiitic metabasalt and hybrid rocks.

The deposit can be regarded as formerly contact mineralization at the base of an olivine-rich ultramafic rock which has been mobilized during regional metamorphism into a (stratigraphic) footwall basaltic sequence. Segregation of nickel and copper during mobilization is indicated by the high Ni:Cu ratio. The distribution of massive sulphides is probably very irregular in detail.

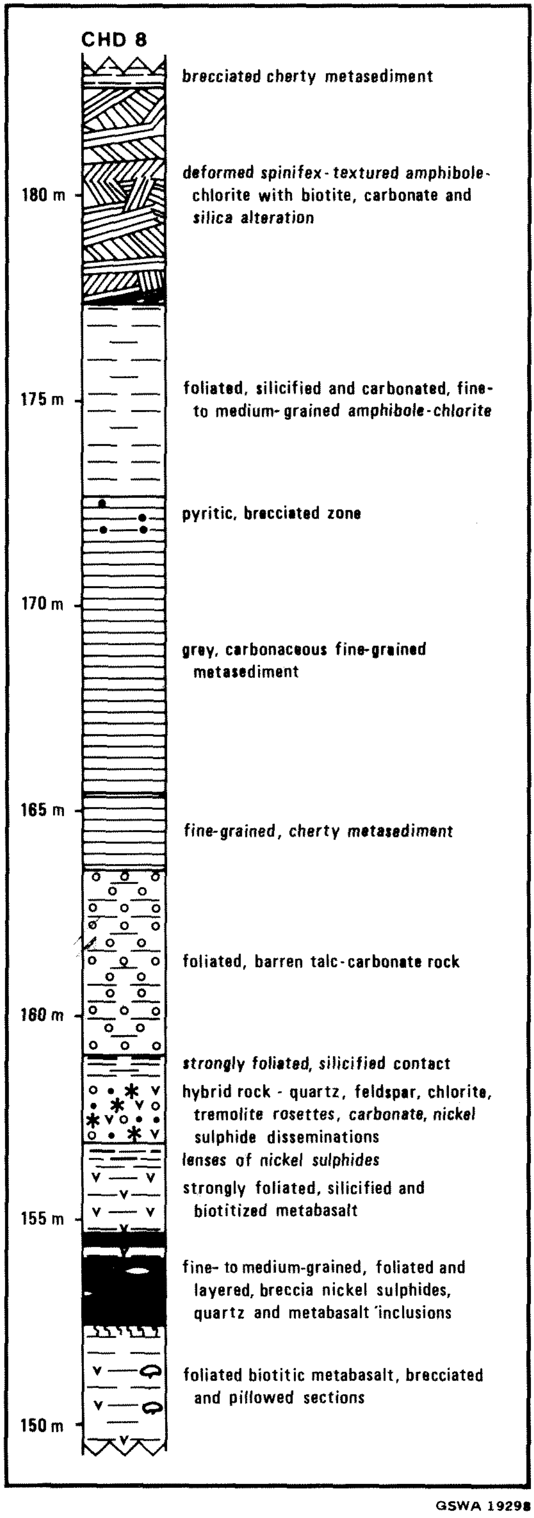


Figure 72. Diagrammatic geological log of part of diamond drill hole CHD 8, Carnilya East deposit.

OTHER PROSPECTS IN THE CARNILYA AREA

These prospects are described from east to west and all except the last-mentioned are in the Carnilya ultramafic formation (Fig. 71).

The 31 800E prospect is 1.5 km east-southeast of Carnilya East deposit where the ultramafic formation terminates, surrounded by metabasalt. Small outcrops of gossanous material occur over a distance of 30 m in oxidized tholeiitic metabasalt, 30 m southwest of the ultramafic rock. Percussion drilling by WMC encountered small amounts of nickel sulphides and indicated that the ultramafic rocks also terminated at shallow depth.

In the Laterite Hill area, 2.5 km east of Carnilya Hill deposit, BHP discovered traces of nickel sulphides in talc-chlorite schists and carbonated serpentinite dipping southeastwards. The best intersection in diamond drillcore was 0.24 m assaying 0.8 per cent nickel. There is some silicate nickel enrichment in the lateritic profile here, with intersections of up to 16 m averaging 1.03 per cent nickel being recorded.

The 8L Anomaly is 1.8 km east of Carnilya Hill deposit. A gossan 70 m long and 0.3 m wide was delineated by BHP using costeans. The gossan occurs at the base of the second ultramafic flow, 80 m above the base of the Carnilya ultramafic formation, which dips south at 40 to 60 degrees. Two out of five percussion drillholes intersected oxidized nickel-copper sulphides, and Heath and Arndt (1976) interpreted the prospect as the remnant of a small hangingwall orebody largely removed by erosion. Another gossan found 60 m to the northwest, probably at the base of the third ultramafic flow, also seems to represent an isolated occurrence of mineralization. One percussion drillhole sited below the gossan intersected 2.03 m of nickel sulphides assaying 1.1 per cent nickel and 0.12 per cent copper (Heath and Arndt, 1976).

Finally, the Area 7 prospect is located 5 km west-southwest of Carnilya Hill deposit in an ultramafic formation situated 1 to 2 km south of the Carnilya ultramafic formation. The regional geology suggests that the two formations might be the same, being repeated by an anticline inclined towards the south (Fig. 71). The ultramafic rocks dip south and become less magnesian southwards. Exploration was carried out by Great Boulder in the late 1960s and their work was re-assessed by WMC in 1976-1977. Disseminated nickel sulphides were found in the basal flow of the ultramafic formation where the formation thickens locally to about 140 m. Several mineralized zones up to 120 m long and 15 m wide occur in talc-carbonate rocks, but the best mean grade of these zones is 1.4 per cent nickel. Pyrrhotite, violarite and chalcopyrite are the sulphide minerals.

HALLS KNOLL PROSPECT (31°55′10″S; 121°50′40″E)

Halls Knoll prospect is 31 km north-northeast of Norseman on the eastern shore of a large peninsula ('Killaloe' or 'Polar Bear' peninsula) which projects northwards into Lake Cowan. Mafic to ultramafic rocks strike northwest and are cut by a major fault of similar orientation which passes about 1 km west of the prospect. Gemuts and Theron (1975) equated the mafic to ultramafic rocks with those at Widgiemooltha (their Sequence 3), but Williams (1976) favoured a correlation with a younger assemblage (his Kalpini Group). The rocks dip and become younger towards the northeast. Serpentinite, talc-carbonate and tremolite-chlorite rocks contains metasedimentary layers and units of metagabbro (Eshuys, 1975). Anaconda discovered a malachite-stained gossan on a small island just off a small headland projecting eastwards from the peninsula. The gossan, in talc schist associated with a metasediment, was tested by nine percussion drillholes (751 m total). Nickel sulphides were encountered in four drillholes, the best intersection being a 1.22 m width averaging 1.14 per cent nickel. Only one drillhole penetrated the basal contact of the ultramafic rocks, but this was barren.

Sulphides also occur in serpentinite which crops out at the small headland. Anaconda drilled three percussion drillholes into the serpentinite but the highest assay was 0.46 per cent nickel. Unimin re-examined the occurrence and reported the presence of millerite, accompanied by pyrrhotite, chalcopyrite and pyrite, in the outcrop (Eshuys, 1975). A diamond drillhole intersected similar mineralization at depth within the serpentinite; no mineralization was found at the basal contact of the serpentinite. The best intersection was a 1.28 m true width averaging 0.87 per cent nickel and 0.01 per cent copper.

PIONEER PROSPECTS (31°48′25″S; 121°37′10″E)

The Pioneer nickel prospects are 27 km north-northwest of Norseman, on the eastern flank of the Pioneer dome, a syntectonic structure occupied by granitoid and gneiss (Cox and Tyrwhitt, 1975; Archibald and others, 1978). Thin assemblages of mafic to ultramatic rocks occur in an east-dipping sequence of clastic metasedimentary and felsic metavolcanic rocks.

The prospects are situated in a mafic to ultramafic assemblage in contact with gneissic rocks of the Pioneer dome. Foliated hornblende-plagioclase amphibolites up to 500 m thick are overlain by lenticular ultramafic units commonly about 200 m thick. Metasedimentary schists succeed these ultramafic rocks but may include additional ultramafic lenses (see Cox, 1975, Fig. 3). Regional metamorphism attained high amphibolite facies conditions, and most rocks have a thoroughly recrystallized dynamic metamorphic texture. Peletic schist may contain garnet, sillimanite and andalusite. Porphyroblastic metamorphic olivine and enstatite occur in some olivine-rich ultramafic rocks. Though flattened, spinifex texture is preserved in some actinolite-chlorite schists and irregular porphyroblasts of metamorphic olivine may be superimposed on this texture (Oliver and others, 1972). The ultramafic units become less magnesian upwards (eastwards) and contain several horizons of black slate; Cox and Tyrwhitt (1975) regarded the units as extrusive. Nickel sulphides occur at the basal contact of some units. The ultramafic rocks are poorly exposed but residual soils make geochemical exploration effective (Cox, 1975; Hall and others, 1973).

Exploration in the area has been carried out by Newmont (managers) in joint venture with NGM in the period 1968 to 1971. Gossans assaying up to 1.1 per cent nickel and 0.7 per cent copper were found at two localities, 1.5 km apart along strike, on the basal contacts of the first series of ultramafic lenses below the base of the metasedimentary sequence. The northern prospect, called JH, consists of two separate shoots at or near the basal contact: (a) a northern shoot 115 m long, up to 6 m thick, with a dip (40 degrees east) length of 180 m; and (b) a southern shoot 60 m long, up to 1.6 m thick and with a dip length of 180 m. The host ultramafic unit (mainly a mottled textured metamorphic olivine/serpentine + tremolite rock) also wedges out downdip, a short distance beyond the termination of the mineralization. At the southern prospect, called BB, one shoot occurs 15 m above the basal contact and is 90 m long, up to 3 m thick, and has a plunge (35 degrees towards the north-northeast) length of about 110 m. At both prospects the mineralization is irregular, forming lenses, veins and stringers of marcasite after pyrrhotite and violarite after pentlandite. Associated finely disseminated sulphide is less altered and consists of pyrrhotite, pentlandite and chalcopyrite. Oxidation is complete to a depth of about 40 m. The average grade of the shoots is 1.1 per cent nickel and 0.1 per cent copper. Some 32 500 t of mineralization at this grade is indicated for the JH prospect.

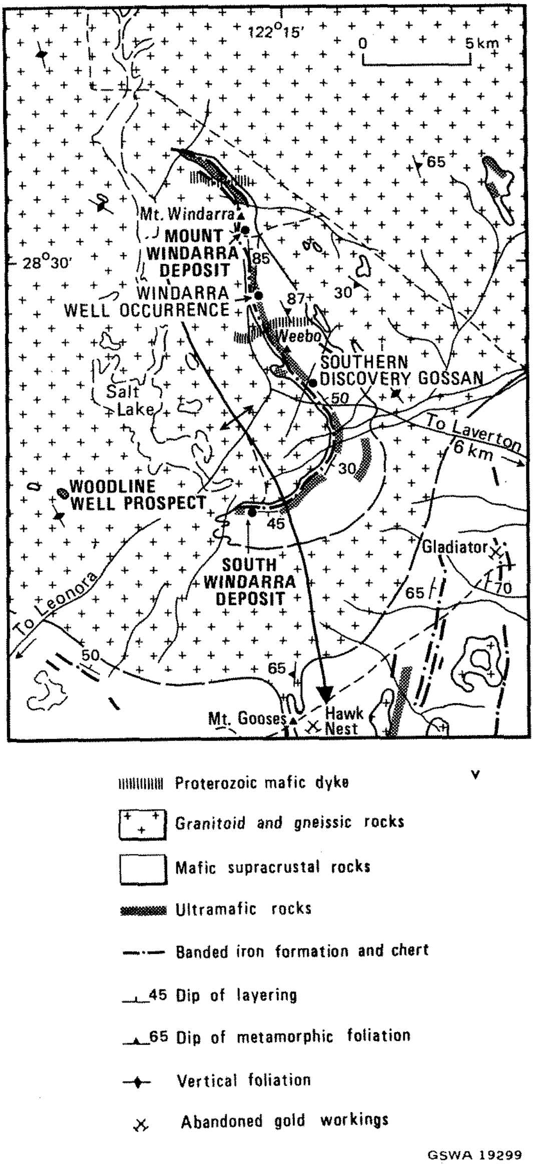


Figure 73. Geological map of the Windarra group of deposits.

WINDARRA GROUP

GEOLOGY

INTRODUCTION

The nickel deposits of the Windarra group are located some 250 km north-northeast of Kalgoorlie, near the eastern margin of the Norseman-Wiluna belt. The group is conspicuous in that it is isolated from all other nickel deposits, which are found in the western half of the belt. The deposits occur in an arcuate remnant of mafic to ultramafic rocks to the northwest of Laverton (Fig. 73).

Exploration in the northern part of the supracrustal remnant was carried out by Poseidon from 1969 to 1971. In the southern part, which lacks outcrop, the Union Oil – Hanna – Homestake consortium undertook exploration in 1970 to 1971, followed by Poseidon from 1972 onwards. The early exploration is described by Robinson and others (1973). Since mid-1975 WMC has managed exploration and mining. Regional geological studies include those by Hobson and Miles (1950), Gower (1976) and Goss (1977). The geology of the nickel-bearing rock sequence is summarized by Roberts (1975) who cites specialized studies on the Mount Windarra deposit undertaken by university students (Davidson, 1970; Drake, 1972; Drew, 1971; Leahey, 1973; and Watchman, 1971). An important contribution on the petrology and mineralization of the South Windarra deposit was made by Santul (1975). Dwyer (1977) and Goss (1977) described the internal stratigraphy of the mineralized ultramafic formation. Aspects of the ore petrology of the Mount Windarra deposit with special reference to tectonometamorphic effects and sulphur isotope studies, are discussed by Barrett and others (1977) and Seccombe and others (1978) respectively. A paper by Schmulian (1982) is the most recent review of the geology at Windarra.

Regional metamorphism attained mid-amphibolite facies conditions (ca. 500-550°C, 400 MPa) as deduced by Drake (1972) and Barrett and others (1977). Dynamic metamorphic textures are typical, but static igneous and overprint textures are also found.

STRATIGRAPHY

In the regional context, Gower (1976) and Williams (1976) equated the mafic to ultramafic sequence at Windarra with the oldest mafic to ultramafic formation in the Norseman-Wiluna belt, the Morelands Formation. If correct, this means that these rocks are older than the Kalgoorlie-Kambalda mafic to ultramafic sequence. However, there is not a consensus regarding the internal stratigraphy of the Windarra-Laverton area. Gower and Williams both implied that the stratigraphy of the Morelands Formation equivalent does not simply become younger southeast, outwards from the core of the Margaret anticline. In contrast, Goss (1977) proposed a non-repetitive stratigraphy from ultramafic rocks at the base, at Windarra, up into mafic and finally clastic metasedimentary rocks at Laverton. The important consequence of Goss' scheme is that nickeliferous ultramafic rocks are confined to the base of the succession (the 'Windarra sequence') which is only developed in the core of the Margaret anticline at Windarra.

The stratigraphy of the Windarra ultramafic sequence is summarized in Table 43. In broad terms it can be compared with the Kambalda sequence, the most notable difference being the lack of a footwall basaltic formation and the presence of a thick banded iron-formation at Windarra. There are considerable variations in the ordering and thickness of the sequence along strike, particularly in the mineralized areas, but an overall upward trend of decreasing magnesia content is characteristic. Geochemical profiles and the distribution of remnant spinifex and cumulate textures indicate that most ultramafic rocks are probably extrusive (Santul, 1975; Dwyer, 1977; Seccombe and others, 1978). Dwyer (1977) pointed out the difficulty of detecting flow tops in thick, metamorphosed olivine

TABLE 43. GENERALIZED STRATIGRAPHY OF THE WINDARRA ULTRAMAFIC SEQUENCE

Informal name	Lithology	Approx thickness (m)
(9) Upper hangingwall ultramafic	Tremolite-chlorite schist, some talcose; occurs within (8)	0-20
(8) Hangingwall metabasalt No 2	Komatiitic and tholeiitic metabasalt (foliated or massive amphibolite)	700-5000
(7) Hangingwall ultramafic zone	Mainly metapicrite (tremolite-chlorite rocks), some grades into metabasalt	0-320
(6) Hangingwall metabasalt No 1	Metabasalt or amphibolite, 8 to 12% MgO, amygdaloidal at South Windarra	>200
(5) Hangingwall metasediment	Layered quartz-amphibole ∓ magnetite ∓ Fe sulphide ∓ carbonate ∓ plagioclase ∓ biotite; rarely contains nickel sulphides (F shoot); variable; absent at South Windarra; occurs within (4)	20
(4) Windarra ultramafic formation	(c) Metapicrite, accounts for bulk of ultramafic away from nickel deposits; more magnesian near deposits	up to 300
	(b) Metaperidotite: chlorite-amphibole serpentinite, talc-dolomite; best developed near nickel deposits	
	(a) Meta-olivine peridotite: serpentinite and talc-magnesite + dolomite; host to nickel deposits and confined to mineralized areas	
(3) Footwall metasediment	Layered; variable petrology like (5) some chlorite-actinolite ∓ talc ∓ biotite; represented(?) by lenticular quartz (recrystallized chert) grit to conglomerate; absent at South Windarra	0-90
(2) Corridor ultramafic	Foliated talc-chlorite-carbonate, some serpentinite	0-50
(1) Main banded iron-formation (BIF)	Layered quartzose rocks with variable combinations of actinolite, grunerite, magnetite pyrite, clinopyroxene, biotite, hornblende, almandine, riebeckite and sphene	20-150

Data from Goss (1977) with additions

peridotite units at Mount Windarra, because of thin (about 1 m) A zones which lack coarse, platy spinifex textures. The mineralized olivine peridotite flows range from 25 to 130 m in thickness. Peridotites have thicker A zones, and many picritic flows are of the coarse to fine polygonally jointed type (the massive flows of Arndt and others, 1979). The less magnesian ultramafic flows tend to be thinner (5 to 25 m). Preservation of igneous textures is common in serpentinites, but most talc-carbonate rocks have dynamic igneous to metamorphic textures and are therefore foliated.

The basaltic components of the Windarra ultramafic sequence seem to be of mixed tholeiitic and komatiitic affinities. They consist of hornblende or actinolite, quartz and altered plagioclase, with accessory chlorite, carbonate, sphene, epidote, garnet, and biotite. These rocks are commonly strongly foliated and lineated.

There are three metasedimentary units in the sequence, numbered (1), (3) and (5) in Table 43. The main banded iron-formation (BIF) is the only unit with lateral persistence. The footwall metasediment proper is confined to the area of the Mount Windarra deposit. The quartz grit to conglomerate is restricted to the outcrop south of Windarra Well and, though it commonly occurs at a similar stratigraphic horizon, it is not suggested that the clastic rocks are a facies equivalent of the footwall sediment. Locally the grit to conglomerate unit rests directly on the main BIF, and the oligomictic nature of the clastic rocks suggests a local derivation. Recrystallized banded chert clasts resemble much of the main BIF outcrop. The hangingwall sediment is even more localized in distribution, being patchily developed at the top of the main olivine peridotite at Mount Windarra.

The petrology of the three metasedimentary units is similar: vertical and lateral variability are characteristic, and the presence of magnetite-bearing and sulphidic facies is common to all. Limited chemical information confirms the similarity of some components of each unit (Drake, 1972; Santul, 1975; Groves and others, 1979), although in general, where not sulphidic, the main BIF is probably more iron-rich and less aluminous than amphibole-bearing non-sulphidic varieties of footwall and hangingwall metasediments.

Strongly deformed and recrystallized granitoid rocks enclose the Windarra supracrustal remnant. These rocks are of adamellitic to granodioritic composition, although a muscovite-rich granitoid is a local variant at South Windarra. Sodic dolerite-gabbro dykes, now metamorphosed to hornblende or actinolite - quartz - altered plagioclases + magnetite assemblages, have intruded the Windarra ultramafic sequence and the granitoids. Most dykes have an orientation between north and northwest. The mafic dykes are generally post-dated by metamorphosed feldspar porphyry dykes which have a sodic composition similar to that of the porphyries at Kambalda.

Metasomatic reaction zones rich in biotite, phlogopite, chlorite, tremolite or talc are developed along contacts between ultramafic rocks and both types of dykes, and ultramafic rocks and metasedimentary units.

STRUCTURE

The Windarra supracrustal remnant is folded by the Margaret anticline, a major structure which plunges moderately southwards (Fig. 73). The layering and sub-parallel metamorphic foliation dip to the east-northeast at 65 to 85 degrees (with local overturning) on the eastern limb of the anticline, but dips decrease to 30 to 55 degrees in the axial zone. Woodline Well prospect is a small inclusion of mineralized mafic to ultramafic rocks in gneissic granitoid rocks, which is regarded as a remnant of the western limb. Here dips are subvertical and the strike is west-northwest.

In the main BIF exposed on the eastern limb of the Margaret anticline at Mount Windarra, steeply-plunging, similar to concentric folds of dextral symmetry are abundant. Plunge angles are in the range 60 to 85 degrees towards the north-northwest, except to the Mount Windarra deposit where the folds plunge to the south-southeast. The fold at Mount Windarra is the largest example of this type, and the steep (80-85 degrees) southerly plunge is shared by the individual ore shoots (Figs 74 and 75). Penetrative mineral lineations, mullion structures and rodded quartz are well developed in the main BIF and the immediately overlying ultramafic unit and these structures are parallel to the steeply plunging folds at Mount Windarra or are oriented downdip at South Windarra. Stretched

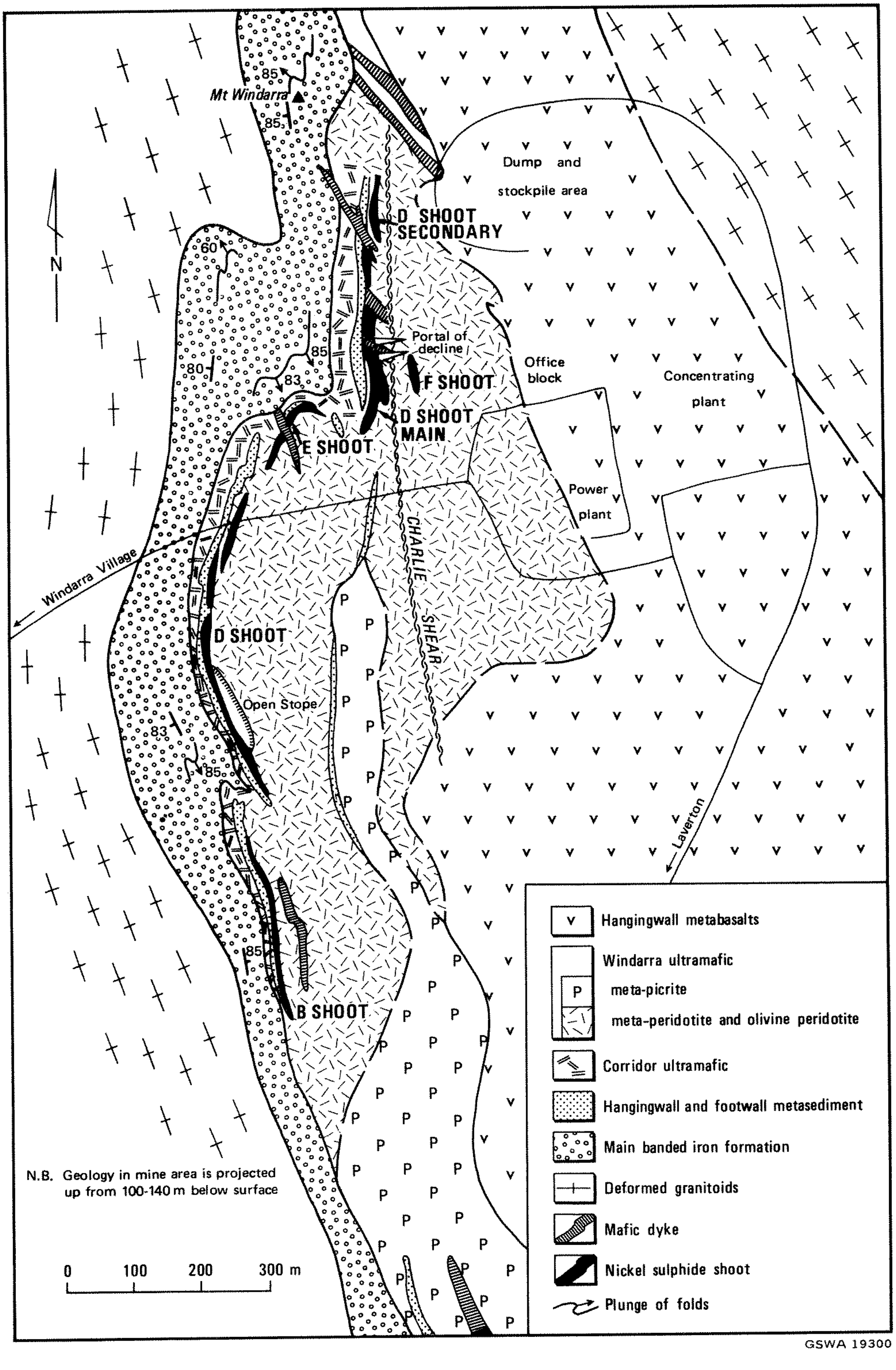


Figure 74. Geological map of the Mount Windarra deposit.

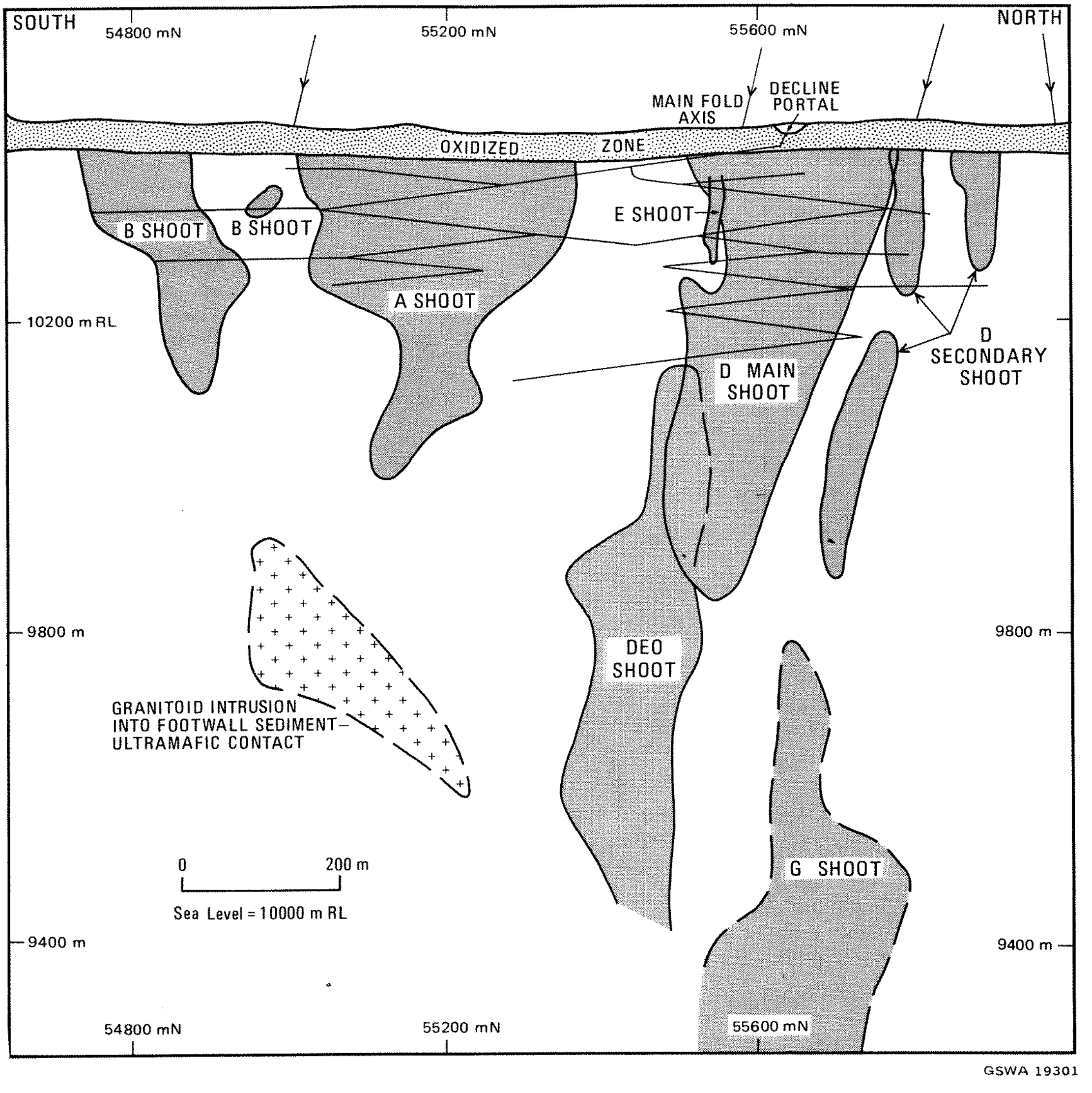


Figure 75. **Vertical longitudinal section projection (looking west) of the Mount Windarra deposit showing plunge of ore shoots and of folds in the main BIF.**

pebbles in the conglomerate at Windarra Well also have long axes plunging steeply south. A metamorphic cleavage, axial planar to these folds, develops in some hinge zones but is not pervasive.

The meta-basic dykes have exploited the axial regions of these folds at Mount Windarra and of the Margaret anticline at South Windarra (Figs 74 and 76). However the dykes are commonly truncated at ultramafic-metasediment contacts which demonstrates late movement at the base of the ore zone, a common feature in some shoots at Kambalda also. Another late tectonic feature may be subhorizontal flexures, which result in west-dipping segments of the mineralized footwall metasediment-ultramafic contact at Mount Windarra, in a similar fashion to like structures at Nepean. Small, subhorizontal flexures also occur at South Windarra in the basal ultramafic – main BIF contact zone, and these flexures may also deform the intrusive dykes and their schistose marginal metasomatic reaction zones.

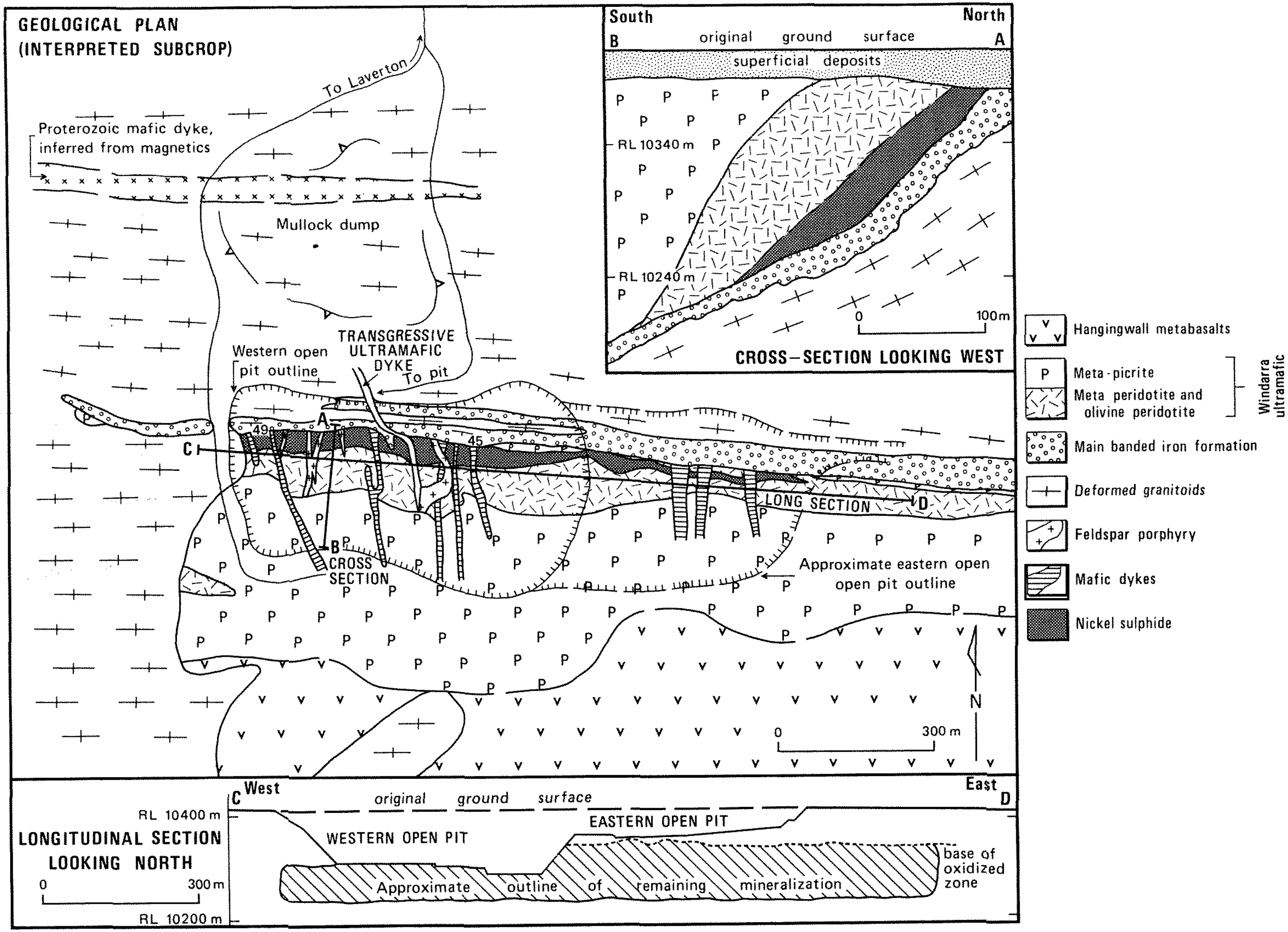


Figure 76. Geological plan (interpreted subcrop), cross section and vertical longitudinal section projection of the South Windarra deposit.

MINERALIZATION

GENERAL

Of the total pre-mining, identified reserve of contained nickel at 1 per cent cut-off (184 700 t), some 66 per cent occurred at the Mount Windarra deposit and 34 per cent was accounted for by the South Windarra deposit. Most mineralization of economic importance is found at the base of olivine peridotite units. At Mount Windarra about 95 per cent of the pre-mining nickel reserve is sited in the first such unit above the footwall metasediment. The remainder is in or associated with the hangingwall metasediment. At South Windarra the bulk of the mineralization occurs at the basal contact of the Windarra ultramafic unit with the main BIF; low-grade hangingwall mineralization is found at the base of the second olivine peridotite unit above the main BIF contact. The general setting of the deposits is unique, being characterized by an intimate association with iron-rich metasedimentary rocks, and the predominance of hangingwall ores (i.e. mineralization not at the base of the ultramafic formation).

Production from the decline mine at Mount Windarra and the open cut mine at South Windarra began in late 1974 and total official production to closure in the first half of 1978 amounted to 37 340 t of contained nickel. Further details of production history are given in Chapter 1. Investigation of the Woodline Well prospect has not proceeded beyond the drilling stage, but available resources are very small.

The nickel sulphide shoots consist overwhelmingly of fine- to medium-grained disseminated sulphides (Fig. 90B) with small amounts of breccia and massive to matrix sulphides. Patches of blebby sulphides and poorly developed triangular-textured sulphides are rare. The breccia sulphides are commonly developed at the basal contact of shoots and comprise fragments of foliated and folded sulphidic metasediment or metasomatic reaction zone rocks in a matrix rich in iron sulphides (Fig. 91A). Massive sulphide (Fig. 89B) is also commonest at the base of the ore section where it grades into breccia sulphide in many places. Some massive sulphide contains coarse mineralogical layering in addition to a fine-scale foliation defined by small gangue inclusions and optically and dimensionally oriented pyrrhotite. Pyrite and/or chalcopyrite may be concentrated at the edges of massive sulphide or in veins into the wall rocks. The footwall metasediment (or to a lesser extent the main BIF at South Windarra) may also constitute ore locally where the nickel grade exceeds 1 per cent, and in this case the 'metasedimentary or BIF ore' is commonly overlain by breccia or disseminated sulphides. Even where not ore grade the main BIF generally has an abnormally high nickel content (e.g. 500 ppm), suggesting that some nickel may have migrated from the overlying ultramafic rock (Watchman, 1971; Santul, 1975) or that some nickel could be of volcanic-exhalative origin (Seccombe and others, 1978).

Monoclinic pyrrhotite and pentlandite with lesser pyrite and chalcopyrite are the chief primary sulphide minerals. Magnetite, chrome-magnetite, chromite and ilmenite accompany the sulphides. Millerite is a rare phase in some disseminated sulphide at South Windarra. Disseminated ore generally contains between 0.5 and 5.0 per cent nickel, with the lower value corresponding to a natural cut-off figure in many places. The pyrrhotite:pentlandite ratio in disseminated ore is about unity. Massive ore returns assays of between 6 and 16 per cent nickel, has higher pyrrhotite:pentlandite ratios and is consequently more iron-rich than disseminated ore. Breccia and metasedimentary ores are correspondingly even more iron-rich. Breccia ore contains up to 8 per cent nickel, being richest where it grades into massive ore; pyrrhotite or pyrite is the dominant sulphide phase. Metasedimentary ore is commonly adjacent to breccia ore and has a similar but more iron-rich sulphide mineralogy.

Bulk Ni:Cu ratios for Mount Windarra and South Windarra are 11 and 22 respectively. The higher value for South Windarra may partly relate to the slightly more magnesian composition of the host unit (Fig. 15). The individual shoots at Mount Windarra have a range in bulk Ni:Cu ratios from 8.5 to 17. Massive and breccia ores have very variable Ni:Cu ratios caused largely by preferential migration of copper during regional metamorphism.

MOUNT WINDARRA DEPOSIT
(28°29′10″S; 122°13′50″E)

General

The deposit was discovered in April 1969 by K.G. Shirley who was prospecting aeromagnetic anomalies and associated ultramafic rocks in the Laverton area for Poseidon (Robinson and others, 1973). A little earlier he had found a small malachite-stained nickel gossan in a talc-carbonate rock 8 km south of Mount Windarra at the 'southern discovery gossan, (Fig. 73). Subsequent drilling failed to locate economically important mineralization either here or at Windarra Well where gossanous material was also found. The first discovery at Mount Windarra was of small gossan outcrops amongst BIF scree material at A shoot (Shirley shoot). A sample of gossan analyzed by Travis and others (1976) contained 0.16 per cent nickel, 0.19 per cent copper, 1 326 ppb palladium and 37 ppb iridium.

Nickel sulphides were encountered during percussion drilling of A shoot in September 1969, and the presence of a second shoot (B shoot) to the south was indicated. The subsequent share boom, during which Poseidon's shares rose from $1.15 to $280, and a spate of other nickel exploration companies were floated, is documented by Sykes (1978).

When diamond drilling to test A shoot at depth began in December 1969, percussion drilling of the contact zone northwards was also commenced. This resulted in the discovery of D and E shoots. The blind DEO (Deeper Eastern Ore) and F shoots were discovered by diamond drilling in late 1970. The last shoot to be found — G shoot — was also blind, and was partly outlined by deep diamond drilling in 1977. Work on establishing a decline mine complex began in May 1971 and production eventuated in September 1974 based on demonstrated reserves of 5.6 Mt averaging 1.93 per cent nickel (108 000 t contained nickel) at a 1 per cent cut-off. By then the Windarra nickel project (Mount and South Windarra mines) was half owned by WMC, and Poseidon (through its subsidiary Windarra Nickel Mines Pty Ltd) remained managers until July 1975 when WMC gained that position. Production by sub-level open stoping, shrink stoping and cut and fill methods proceeded until June 30, 1978 (Table 2), when the mine was placed on a care and maintenance basis while exploration and development work carried on. Subsidence associated with open stoping has reached the surface at A and E shoots.

TABLE 44. PRE-MINING DEMONSTRATED RESERVES (UNDILUTED) FOR THE MOUNT WINDARRA SHOOTS (1978)

Shoot	Ore (t)	Nickel (%)	Copper (%)	Ni:Cu	Contained nickel (t)	Size order
A	1 613 572	2.20	0.26	8.5	35 499	2
B	355 130	2.10	0.21	10	7 458	5
C	88 766	1.60	0.12	13	1 420	8
D	2 196 752	2.04	0.16	13	44 814	1
DEO	1 044 931	1.64	0.12	14	17 137	3
E	314 944	2.47	0.23	11	7 779	4
F	298 138	1.87	0.11	17	5 575	6
G	223 065	1.31	0.13	10	2 922	7
	6 135 298	*2.00*	*0.18*	*11*	*122 604*	

Calculated using a 1 per cent nickel cut-off figure.

In 1975, the first year of full production, bad ground conditions severely limited the actual production. A partial collapse of a floor pillar in the D shoot workings hampered the production target in 1976. Financial losses forced Poseidon into receivership in October 1976, and eventually this company's half share in the project was purchased by Shell in August 1977. The project received yet another setback in November 1977 when mining operations in A shoot were curtailed by the failure of a mass blast designed to produce some 230 000 t of broken ore in an open stope. At the time of closure in mid-1978, remaining demonstrated mineable reserves were estimated at 5 638 000 t averaging 1.38 per cent nickel (89 080 t contained nickel) at a 1 per cent nickel cut-off (Table 3). Development work is planned to lengthen and deepen the northern decline system to serve D, D secondary, DEO and F shoots, and eventually the deeper levels of A and B shoots. By mid-1979 the decline was extended to a vertical depth of 400 m. To offset the long haulage distances along the decline a raise-bored haulage shaft may be drilled to a depth of 450 m and an underground crushing station installed.

Stratigraphy

The Windarra ultramafic formation (unit (4) in Table 43) is the key stratigraphic element with respect to nickel mineralization. The metamorphosed peridotite to olivine peridotite components of the formation show a dramatic increase in thickness in the mineralized area (Fig. 74). Meta-olivine peridotite units are host to the ore shoots with the exception of F shoot. These units consist of antigorite serpentinite, substantially converted to talc-magnesite + dolomite + chlorite assemblages. Granular cumulus textures are incompletely preserved in some rocks. Bladed metamorphic olivine is superimposed on the static igneous texture in parts of DEO shoot. The southern shoots (A, B and E) occur in a thin (30 m) olivine peridotite unit at the base of the Windarra ultramafic formation, whereas the northern shoots (C, D, D secondary, DEO and G) are in a unit up to 130 m in thickness. As mentioned before, the A zones of these presumed flow units are very thin (about 1 m) and difficult to recognize, partly because of possible confusion with reaction zones also containing amphibole and chlorite. The bulk magnesia composition of the host units probably averages about 40 per cent, which is similar to the host rocks at Kambalda. Groves and others (1979) estimated that from a bulk composition of 39.5 per cent magnesia, the original olivine phenocryst content of the flow would have been about 60 per cent, based on a liquid containing 23 per cent magnesia and an olivine composition of $Fo_{92.5}$. Less magnesian rocks may occur at the base of the units, and as before, these are probably best interpreted as basal chilled zones. These rocks are more chloritic and mostly lack mineralization.

The footwall metasediment is subdivided into three main variants by Seccombe and others (1978), which are as follows:

(a) quartz-pyrrhotite-pyrite ∓ amphibole ∓ biotite
(b) aluminous hornblende-albite-quartz-pyrrhotite-pyrite ∓ biotite
(c) chlorite-actinolite amphibole ∓ talc ∓ biotite.

Magnetite is a common additional minor phase in any of these variants. Variant (a) is the dominant assemblage in the footwall to A, B and E shoots, whereas variant (b) is most important in the footwall to C, D, DEO (where the metasediment is present) and G shoots, although layers of variants (a) and (c) may make up part of the metasediment. The hangingwall metasediment, which is host to much of F shoot is mainly a variant (b) assemblage. Groves and others (1978) pointed out that the Mount Windarra footwall metasediment differs from other sulphidic metasediment associated with nickel deposits in the Eastern Goldfields region, especially in terms of higher magnesia (mean 12.6 per cent) and nickel (mean 1 270 ppm) contents. The chloritic metasediments at Kambalda (Table 29, column 9) may be nearly comparable in magnesia content, but nickel is much less abundant and zinc is an order of magnitude richer compared with the Mount Windarra average of Groves and others (1978).

Ore distribution and structure

The deposit covers a strike length of some 1 400 m in an irregular arc and is divisible into eight shoots named A, B, C, D, DEO, E, F and G shoots (Fig. 74). The original reserves of these shoots, based on 1978 data, are listed in Table 44. Mining has so far been confined to A, B, D and E shoots. The shoots show a range in physical size (Fig. 75), the amount of nickel contained, and in Ni:Cu ratio. Large portions of A and D shoots, the two largest in terms of contained nickel, have evidently been removed by erosion. The physical sizes of DEO and G shoots may be comparable with D shoot but lower nickel grades produce major differences in the nickel contained in DEO and G shoots. The long axes of the shoots are 100 to 700 m in length and are parallel to steeply south-plunging folds in the main BIF (Fig. 75). However, if an enveloping surface is drawn around the known shoots, the long axis of the whole deposit appears to plunge northwards at a moderate to steep angle (Fig. 75).

Some 95 per cent of the mineralization is in or near the basal contact zone of meta-olivine peridotite units with the footwall metasediment. This percentage includes DEO shoot which is in a similar stratigraphic position but generally has a footwall of meta-picrite; the metasediment may be missing because of non-deposition and/or faulting. Structural disturbance complicates relationships but C and E shoots can probably be regarded as remnants of shoots originally at the usual stratigraphic position. The remaining mineralization is in, or adjacent to, the hangingwall metasediment, in a group of several small drillhole intersections known as F shoot, which lies east of a fault known as 'Charlie shear' (Fig. 74).

Mineralization assaying more than 1 per cent nickel (ore grade) varies from 3 to 18 m in thickness with a mean value of 5.5 m (Roberts, 1975). This mineralization is commonly overlain, and in some places also underlain, by subgrade mineralization containing 0.5 to 1.0 per cent nickel (Figs 77 and 78). Locally, barren (less than 0.5 per cent nickel) ultramafic rock may be interposed as thin (up to 10 m) lenses between subgrade and ore-grade mineralization, a good example being the hangingwall (east) side of A shoot.

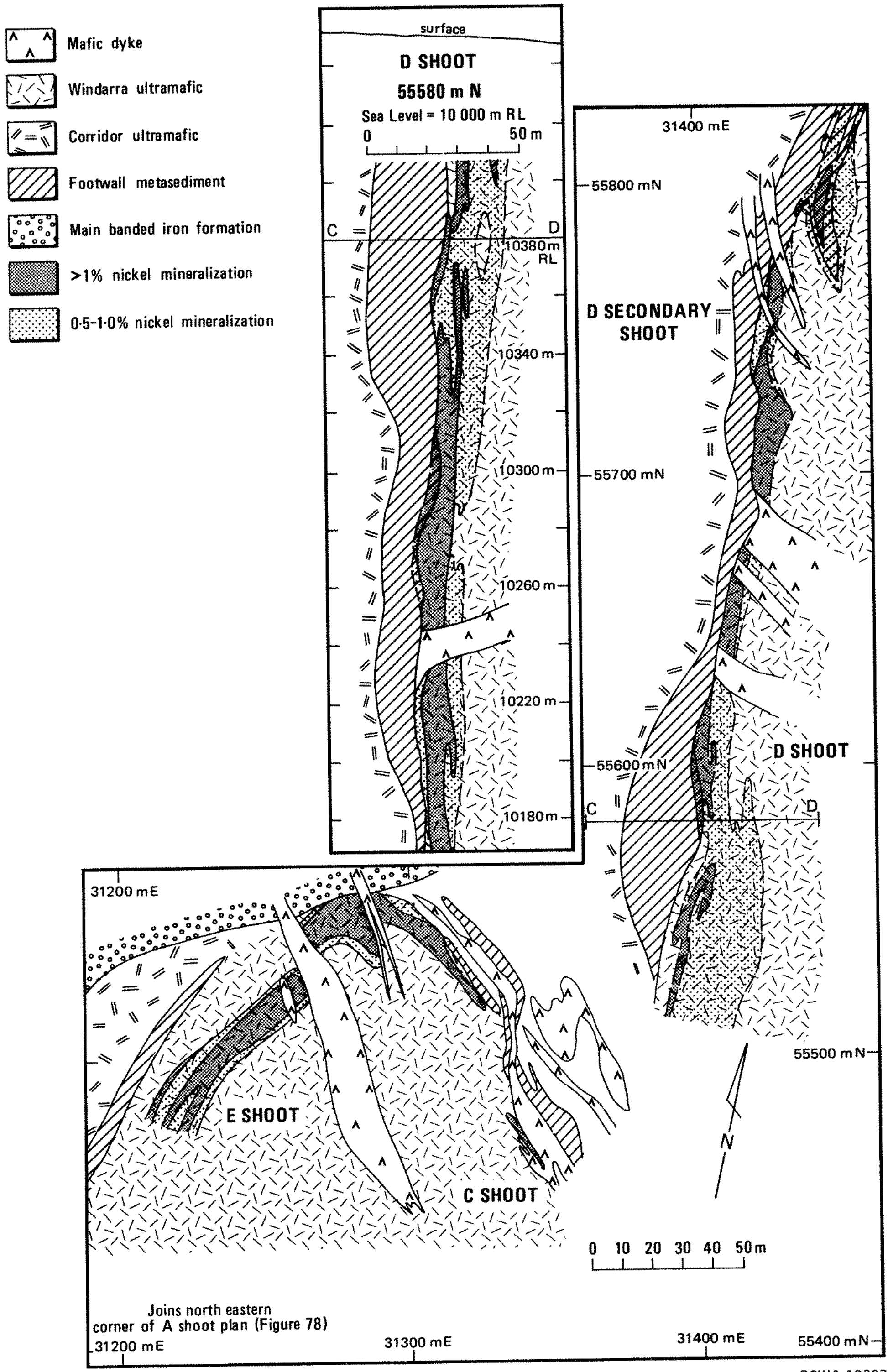
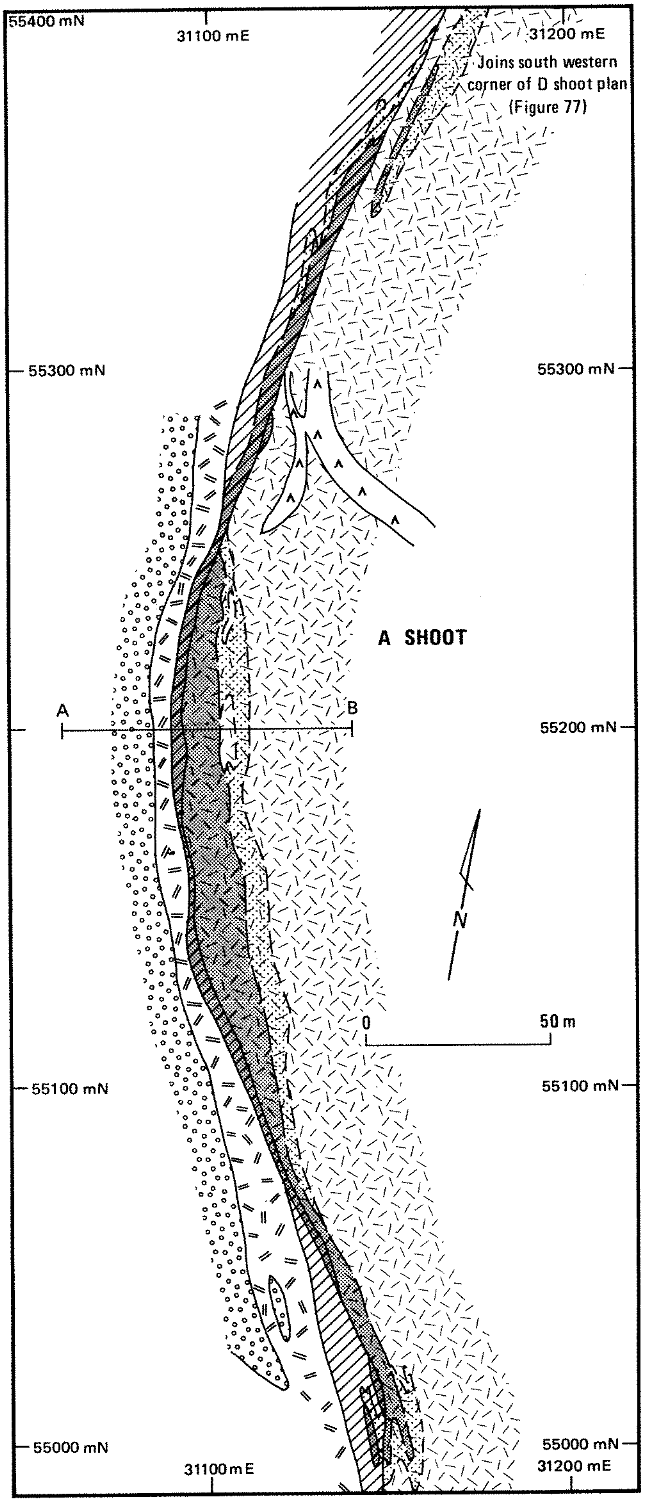


Figure 77. Cross section through D shoot, and plans (at 10 380 m RL, approximately 60 m below surface) of C, D, D secondary and E shoots, Mount Windarra deposit (based on WMC data).



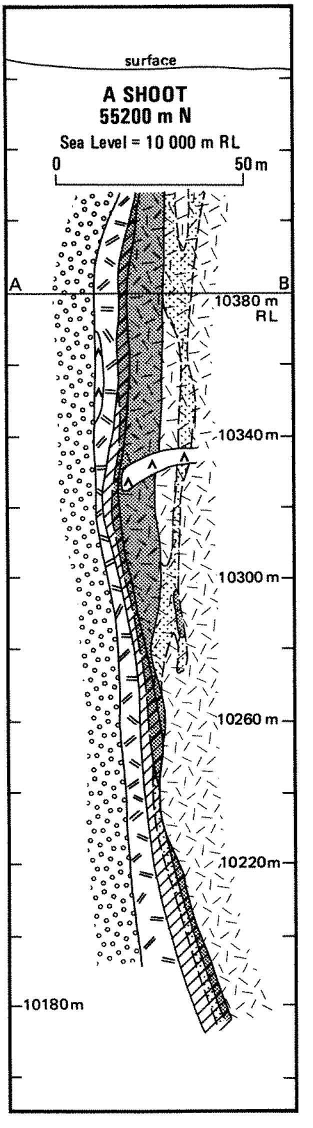


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Figure 78. Cross section and plan of A shoot (at 10 380 m RL, approximately 60 m below surface), Mount Windarra deposit (based on WMC data). Symbols are as for Figure 77.

A few metres of barren, commonly less magnesian ultramafic rock may be interposed between mineralized ultramafic rock and the footwall metasediment, but this is not a typical feature and is generally found only on the ends of shoots (R.G. Wright, pers. comm. 1978).

Because of the folding and faulting of the deposit it is difficult to assess the possible influence of primary structures in controlling ore distribution. However, in the case of A and B shoots, and less obviously D shoot, there is an inverse relationship between ore thickness and the thickness of the footwall metasediment (Figs 77 and 78). The significance of this relationship is not understood, but some possibilities can be raised. If the sites of ultramafic eruption were adjacent to the present positions of the shoots, and the footwall sediment is of partly ultramafic tuffaceous or exhalative origin, then the sediment might be expected to be thickest at its source and the subsequent sulphidic peridotitic flow could preferentially fill hollows between eruptive sites. Alternatively, the peridotitic flow may have melted and assimilated some of the underlying sediment on eruption. This hypothesis seems unlikely as there is no field evidence for such a process (which presumably would have been arrested during cooling), and the sulphur:selenium ratios of disseminated and massive ore in the ultramafic rock contrast markedly with those of the footwall metasediment (Seccombe and others, 1978).

The distribution of individual ore types will now be discussed. Fine- to medium-grained iron-nickel-copper sulphides disseminated in the basal part of the ultramafic rock form the commonest ore types, which may be either little deformed (e.g. D and DEO shoots) or be foliated and lineated (e.g. A, B, E and G shoots; Fig. 90B). Irregular lenses and veins of massive ore occur at the base of the ore section and appear to be commonest in more deformed environments and adjacent to felsic or mafic dykes (e.g. A, B and E shoots).

Two ore types involve the footwall metasediment, particularly where the metasediment is the quartz-pyrite-pyrrhotite variety. Breccia ore consists of fragements of foliated and folded, metasedimentary, metasomatic reaction zone, and ultramafic rocks, in a foliated sulphidic matrix (Fig. 91A). Breccia ore is best developed in the more deformed areas, which, with its internal structure, clearly point to a tectonic origion (Davidson, 1970; Leahey, 1973). Metasedimentary ore normally occurs adjacent to breccia ore. Metasedimentary ore simply consists of sulphidic footwall metasediment which contains on average more than 1 per cent nickel. Breccia and metasedimentary ores may occur beneath, or independently from (i.e. overlain by barren ultramafic), disseminated ore; this is well illustrated by A shoot, the main locus for these ore types (Fig. 78). Both ore types are rarely developed where the *amphibole-rich variants of the footwall metasediment* prevail, as in D shoot, and at the northern limit of A shoot (Seccombe and others, 1978, Fig. 4).

Rare ore types include patchy developments of blebby or triangular-textured sulphides, particularly in antigorite serpentinite (e.g. DEO shoot).

The mineralization of F shoot is described in Chapter 7.

Ore petrology

The deposit is in the oxidized zone to a depth of 37 to 40 m, and supergene sulphides occur to a depth of some 180 m, particularly in breccia and massive ores (Watmuff, 1974). The primary opaque minerals are monoclinic pyrrhotite, pentlandite, pyrite, chalcopyrite, magnetite, chrome-magnetite, ilmenite and rare chromite, sphalerite and galena.

Disseminated ore generally contains between 15 and 25 per cent by volume of sulphides, but rarely becomes a matrix ore with up to 70 per cent sulphides (Roberts, 1975). Pyrrhotite and pentlandite in roughly equal proportions are the chief sulphide minerals, though pyrite is the major iron sulphide in some places. Chalcopyrite is generally present. Chrome-magnetite, and less common composite grains with small relict chromite cores and magnetite rims, are dispersed throughout but tend to be included in the gangue rather than the sulphides. At low sulphide contents the sulphide *minerals tend to be fine grained and evenly disseminated.* In more sulphidic disseminated ore patchy, lenticular and ribbon-like sulphide aggregates occur and the sulphide minerals are fine to medium grained. The sulphide aggregates exhibit static metamorphic intergrowth textures with platy and prismatic silicate minerals in some examples. Pyrrhotite characteristically lacks signs of internal strain except in strongly deformed ore where some kink bands and rare deformation twins may remain in partly annealed pyrrhotite aggregates (e.g. B shoot). Disseminated ore typically assays between 1 and 3.5 per cent nickel, but may contain up to 5 per cent. The mean Ni:Cu ratio for the ore is 14.

TABLE 45. AVERAGE CHEMISTRY OF NICKEL ORES AND CONCENTRATES AT MOUNT WINDARRA DEPOSIT

Weight per cent or ppb*	Composite sample of concentrates[a]	Disseminated ore[b]		Massive ore[b]		Breccia ore[b]		Metasedimentary ore[b]	
	B	A	B	A	B	A	B	A	B
Ni	14.84	1.52	14.7	12.55	13.0	2.18	5.5	0.75	2.4
Cu	1.36	0.11	1.0	0.19	0.2	0.18	0.4	0.10	0.31
Co	0.32	0.03	0.25	0.13	0.14	0.02	0.06	0.01	0.03
Fe	39.5	4.68	45.3	47.90	49.6	21.05	53.0	15.92	50.1
S	43.89	4.00	38.7	35.87	37.2	16.64	41.9	15.00	47.2
Pt*	1 310								
Pd*	3 280								
Au*	901								
Total Pt + Pd + Au	5 491								
Ni:Cu	10.9	14		65		12		7.5	
Ni:Co	47	58		93		91		75	
S:Ni	3.0	2.6		2.9		7.6		20	
Fe:Ni	2.7	3.1		3.8		9.7		21	

Notes:

1. Column A shows mean values of the sulphide fraction of ore.
2. Column B represents data in column A recalculated to 100 per cent sulphides.
3. Sources of data are: a-Ross and Keays (1979); b-Seccombe and others (1978).
4. Seccombe and others (1978) regarded their Ni:Cu ratios for massive, breccia, and metasedimentary ores as being too high, because chalcopyrite-rich samples were avoided during sampling.
5. Ross and Keays (1979) stated that their sulphur value for the concentrate sample is anomalously high because of the inclusion of sulphidic metasediment with ore during mining.

Massive ore is generally coarser grained and more iron- and sulphur-rich compared with disseminated ore (Table 45). Pyrite porphyroblasts up to 15 mm in diameter are common, and pentlandite may form medium-grained porphyroblasts in ores with a low pyrrhotite:pentlandite ratio. Typically this ratio is much higher than in disseminated ore so that fine- to coarse-grained pyrrhotite forms a plentiful matrix. The nickel content of massive ore is between 6 and 16 per cent, with 12 per cent as an average. Pentlandite then tends to be along pyrrhotite grain boundaries. Pyrrhotite is generally elongate and defines a fine-scale foliation along with physically oriented gangue inclusions, but triple-point contacts and polygonization of coarser grains indicate strong annealing recrystallization. However, this recrystallization is not pervasive and some pyrrhotite contains abundant kink bands and fewer deformation twins. The amount of chalcopyrite present is locally very variable, but in general massive ore probably has a higher Ni:Cu ratio than disseminated ore. Coarse mineralogical layering is locally present (e.g. D Shoot). There are no marginal concentrations of spinel phases recorded which could be comparable with massive ores at Kambalda. Magnetite is the chief spinel, but rare zoned chromite-magnetite grains occur.

By an increase in the amount and size of gangue inclusions and in the Fe:Ni and S:Ni ratios, massive ore may grade into breccia ore which is characterized by abundant pyrrhotite. Typical breccia ore contains about 5 per cent nickel. Chalcopyrite is more abundant in breccia ore as indicated by the lower Ni:Cu ratio for ore samples in Table 45 and for A shoot as a whole — the chief repository of breccia ore — in Table 44. Local concentrations of chalcopyrite occur around silicate fragments and in the hinge zones of small-scale folds. Pyrrhotite forms medium-grained polygonal crystals which generally show little if any internal strain because of annealing. Robinson and others (1973) found that pyrrhotite may be more nickeliferous than normal. Pentlandite occurs along grain boundaries and as exsolution lamellae in pyrrhotite. Porphyroblasts of pyrite, similar to those developed in massive ore, may be present. Magnetite and rare composite chromite-magnetite grains are accessory phases.

Metasedimentary ore is correspondingly more iron- and sulphur rich than breccia ore (Table 45). Fine- to medium-grained pentlandite and minor chalcopyrite accompany the dominant pyrite and/or pyrrhotite disseminations or layers in the footwall metasediment. Magnetite is a common accessory but chrome spinels are absent.

The bulk composition of Mount Windarra nickel ore is similar to that of most Kambalda ores in terms of the Fe-Ni-S system (Fig. 34). The value for sulphur for the concentrate sample in Table 45 is considered to be misleadingly high because of the incorporation of sulphidic footwall metasediment into ore during mining (Ross and Keys, 1979).

SOUTH WINDARRA DEPOSIT (28°37′20″S; 122°14′00″E)

General

The discovery of nickel sulphides at Mount Windarra in late 1969 enhanced the potential of the Windarra ultramafic formation to the extent that detailed testing was warranted even where outcrop was completely lacking. The Union Oil — Hanna — Homestake consortium based initital targets for percussion drilling in the South Windarra area purely on magnetic anomalies: the twenty-fifth drillhole intersected oxidized sulphide mineralization averaging 2 per cent nickel in November 1970 (Robinson and others, 1973). This mineralization was concealed below 30 m of alluvium. The basal contact of the ultramafic was delineated more precisely using a proton magnetometer, and in February 1971 nickel sulphides averaging 1.3 per cent nickel over a true width of 13.7 m were encountered in the first diamond drillhole of the subsequent programme. By June 1973 indicated mineable ore reserves to a depth of 174 m were put at 3.2 Mt averaging 1.94 per cent nickel (62 080 t nickel) and 0.09 per cent copper, using a 1 per cent nickel cut-off figure (Roberts, 1975), although subsequent mining was based on a cut-off figure of 0.5 per cent nickel which increased initial undiluted reserves to 10.5 Mt averaging 1.26 per cent nickel (132 300 t nickel).

Following the removal of nearly 6 million cubic metres of alluvial overburden and oxidized rock, open-cut mining of the western, higher grade portion of the deposit began in late 1974. Conventional quarrying methods were used consisting of the establishment of 10 m high benches using airtrac drills and front-end loaders. Production reached a peak of 700 600 t of ore in 1975, but had declined to 562 000 t in 1977 when it was decided to remove overburden from the eastern, lower grade and smaller section of the deposit in preparation for a new open pit (Fig. 76). In the face of adverse marketing conditions production ceased on February 17, 1978. Remaining demonstrated sulphide resources to a depth of 174 m were estimated by WMC to be 2.56 Mt averaging 1.03 per cent nickel (26 830 t nickel) using a cut-off figure of 0.5 per cent nickel.

Stratigraphy

The Windarra ultramafic formation rests directly upon the main BIF at South Windarra. Any equivalents to the footwall or hangingwall metasediment have not been recognized. The metamorphosed peridotite to olivine peridotite components of the formation are thickest where mineralized, and appear to wedge out completely (a) some 2.5 km east of the western end of the deposit; and (b) down dip in the area of the deposit itself (Figs 76 and 80).

The mineralization is within meta-olivine peridotite flow units which have a bulk composition of about 40 per cent magnesia, though much of the B zones of these units average 43 to 44 per cent magnesia (Santul, 1975). Total flow-unit thickness ranges from 35 to 130 m with B zones typically being five times thicker than A zones. The flows are thickest in the west. Antigorite-talc-magnesite/dolomite + chlorite rocks of medium to coarse grainsize are dominant, but varieties more or less affected by talc-carbonate alteration are present. More intense talcose alteration is common marginal to feldspar porphyry and granitoid dykes, and quartz veins. These intrusions also develop tremolite-, chlorite- or biotite-bearing metasomatic reaction zones in the ultramafic rock. Tremolitic rocks containing 25 to 30 per cent magnesia form the A zones of the host ultramafic units. Relict igneous textures are rarely preserved, and in this study spinifex textures were not observed in A zones of the mineralized units, though examples were seen in the metapicrites overlying the lower part of the Windarra ultramafic formation. Slender prisms of serpentinized metamorphic olivine, some several centimetres in length, are a common feature of the B zone rocks, where they represent a static metamorphic texture superimposed on serpentinite with granular static igneous texture. Foliated ultramafic rocks are normally only developed at the base of the ultramafic formation.

The main BIF is up to about 20 m thick and contains quartz, cummingtonite/grunerite, magnetite, biotite, actinolite/hornblende, and almandine in varying combinations, with the addition of pyrite and pyrrhotite at or near the top of the unit particularly.

Intrusive rocks are more abundant than at Mount Windarra, and they include metamorphosed dolerite, albite porphyry, medium- to coarse-grained granitoids and the so-called 'transgressive ultramafic'. The metadolerite and feldspar porphyry are similar to those at Mount Windarra. The porphyries were intruded before and after the dolerite dykes. Most dolerites strike north-south and terminate at the ultramafic - main BIF contact. The granitoids are mainly strongly foliated, biotite adamellite to granodiorite, with some muscovite-rich types present at the west end of

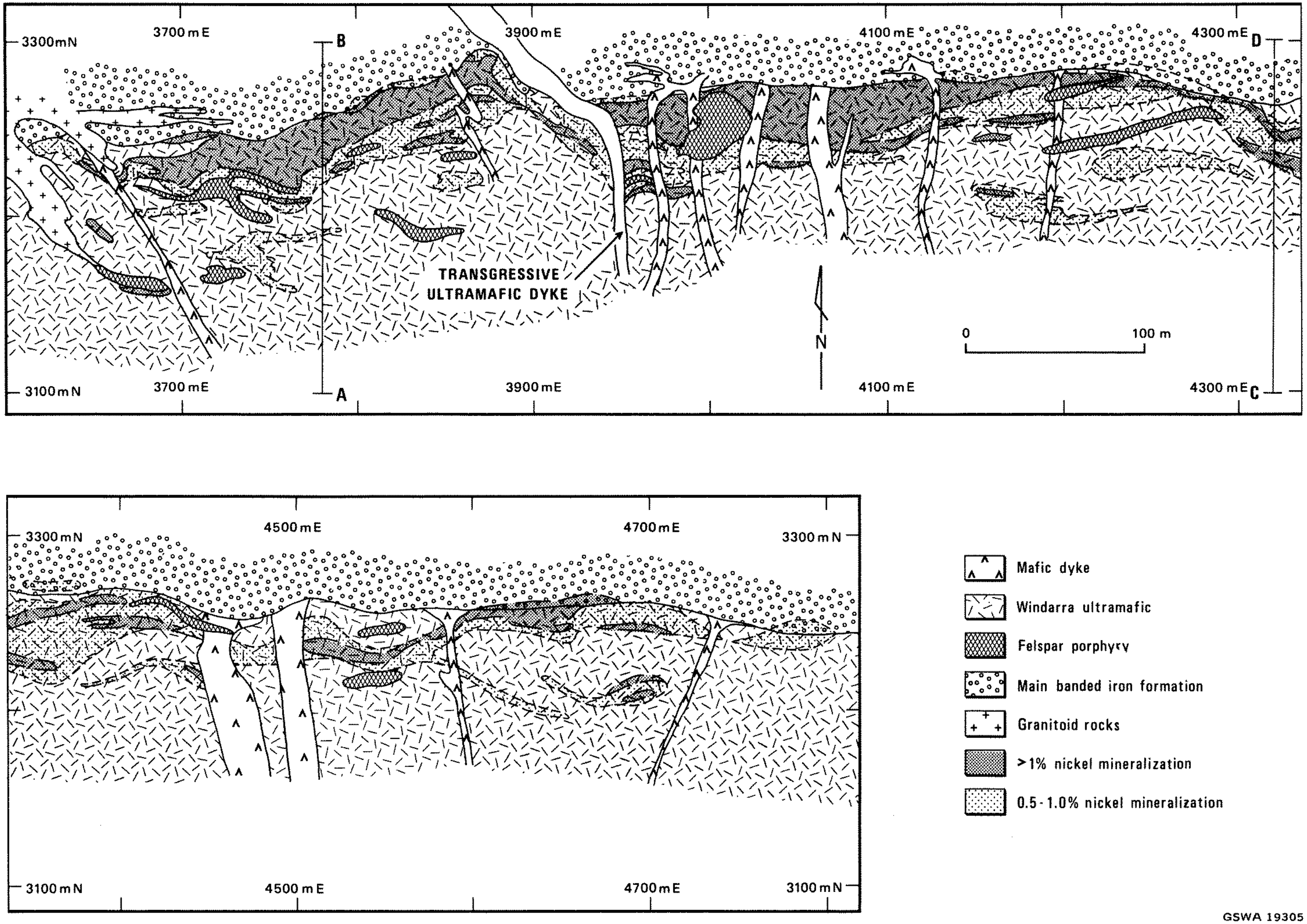


Figure 79. Geological plan of South Windarra deposit at 10 340 m RL (approximately 75 m below surface), based on WMC data.

the deposit. The transgressive ultramafic unit is a persistent arcuate dyke containing hornblende, tremolite/actinolite, biotite, chlorite, quartz and feldspar, and is of picritic composition (Santul, 1975).

Ore distribution and structure

The deposit has a strike length of about 1 200 m and a down dip (40 to 45 degrees) dimension of some 200 m; it is mainly confined to the basal 50 m of the Windarra ultramafic (Figs 79 and 80). A considerable portion of the deposit was removed by erosion before being masked by alluvium. Mineralization assaying more than 1 per cent nickel is only well developed in the western half of the deposit, where it has been exploited by the western open pit (Fig. 76). This mineralization, which attains a thickness of 30 m, is commonly overlain, and locally underlain by lower grade mineralization containing 0.5 to 1.0 per cent nickel. Barren ultramafic rocks may be interposed between mineralization and the ultramafic - main BIF contact, especially in the eastern part of the deposit. There is no obvious structural control of the deposit: irregularities in the strike and dip of the contact are apparently caused by flexural folding. The transgressive ultramafic has exploited a faulted flexural fold which divides the western high grade part of the deposit into two sections (Fig. 79).

Individual ore types are the same as described for Mount Windarra, but breccia and metasedimentary ore types are comparatively rare, being patchily developed in the main BIF. Massive ore is also very limited in extent and is confined to thin basal veins and lenses at the western end of the deposit. The disseminated ore, which constitutes the bulk of the deposit, is mainly restricted to the B zone of the basal flow unit. However, east of the transgressive ultramafic small amounts of disseminated ore are present in the B zone of the second flow unit; this is therefore hangingwall ore.

Ore petrology

The pattern of oxidization is irregular, but in general the oxidized zone extends to a depth of 49 to 73 m below the top of bedrock, the violarite-pyrite zone to 91 to 107 m, and the transition zone up to 250 m (Roberts, 1975). Alteration is more pronounced close to the ultramafic - main BIF contact, and locally violarite-pyrite, transition and primary assemblages may co-exist. The deposit is mainly with the violarite-pyrite and transition zones.

The primary opaque minerals are monoclinic pyrrhotite, pentlandite, pyrite, chalcopyrite, millerite, magnetite, chrome-magnetite and rare chromite, ilmenite, sphalerite and galena. Some molybdenite is present on the contacts of the porphyry intrusions. Disseminated ore generally contains 5 to 15 per cent by volume of sulphides and assays 0.5 to 2.5 per cent nickel, locally increasing to 40 per cent sulphides and about 6 per cent nickel at the basal contact. The major primary assemblage is pyrrhotite and pentlandite with minor pyrite and chalcopyrite. Pyrrhotite:pentlandite ratios probably average about 1 to 1.5. The sulphide minerals occur in aggregates rather than single grains and are fine to medium grained. Well developed static metamorphic intergrowth textures with talc, chlorite and antigorite are exhibited by sulphides and to a lesser extent by spinel phases. Pyrrhotite is anhedral to polygonal and is little strained. Other assemblages include pentlandite-pyrite, millerite-pentlandite-pyrite + pyrrhotite, and magnetite-pyrite-millerite (Roberts, 1975).

Breccia ore consists of fragments of main BIF lithologies, vein quartz, and metasomatic reaction zone and ultramafic rocks in a matrix of pyrite, pyrrhotite, pentlandite and minor chalcopyrite. As at Mount Windarra, pyrite may form medium- to coarse-grained porphyroblasts. Such pyrite also occurs in massive ore accompanied by fine- to medium-grained, annealed pyrrhotite aggregates, pentlandite, chalcopyrite, magnetite and zoned chromite-magnetite grains.

The bulk composition of South Windarra ore is similar to Mount Windarra ore with the exception of a high Ni:Cu ratio (20-22) at South Windarra.

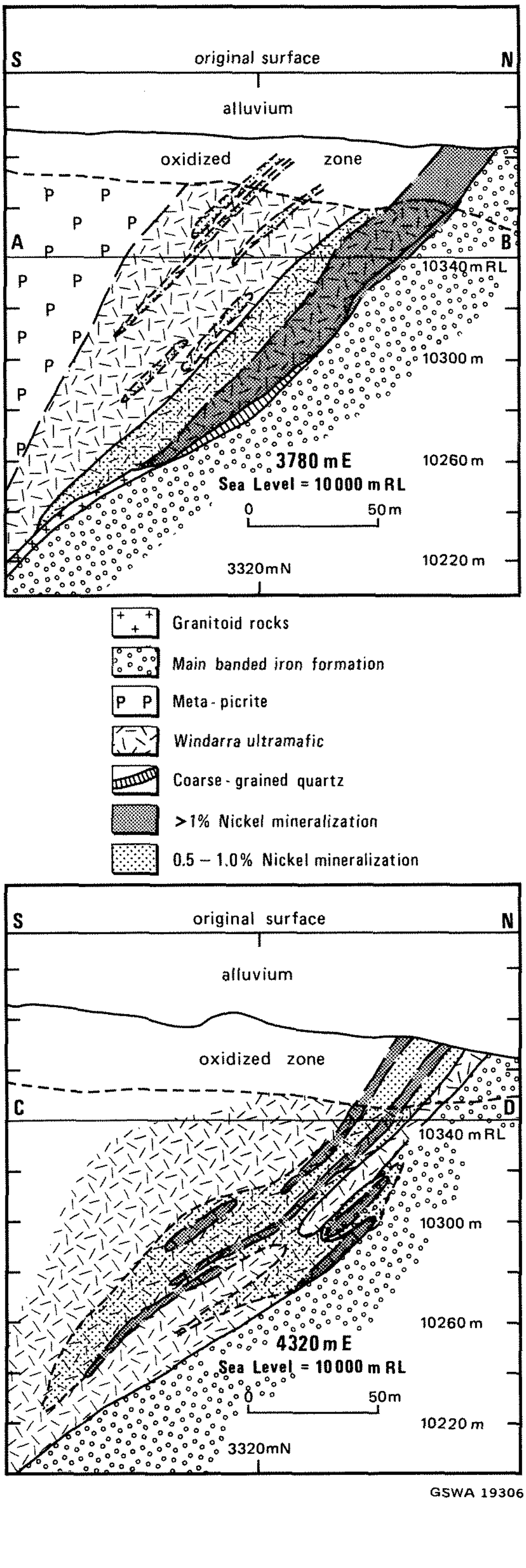


Figure 80. Cross sections through South Windarra deposit, based on WMC data. Location of cross sections and reference are on Fig. 79.

WOODLINE WELL PROSPECT (28°35′50″S; 122°09′35″E)

Woodline Well prospect is 8 km west of the South Windarra deposit, in what is regarded as a small remnant of the main BIF and the Windarra ultramafic formation in gneissic granitoid rocks (Fig. 73). Auger, percussion and diamond drilling by Carpentaria in 1972 indicated that the principal supracrustal remnant is nearly 300 m long, 15 m wide and extends to a depth of about 75 m. The dip is steeply towards the northeast. A few outcrops of amphibolite, hornblendite and talc-tremolite rock occur in a sandy ridge a few metres high. Economically significant mineralization has been intersected in only one diamond drillhole (DDH 1), which assayed 4.23 per cent nickel over a width of 1 m. Fine-grained sulphides (pentlandite-violarite, pyrrhotite) are disseminated within a black, medium- to coarse-grained serpentinized olivine peridotite which preserves bladed metamorphic olivine textures. Diamond drilling intersections downdip of this drillhole and aimed to test for possible plunge directions of the mineralization, failed to find any encouragement.

REMAINING DEPOSITS

MOUNT CLIFFORD GROUP — GEOLOGY AND MINERALIZATION

The Mount Clifford group of deposits is situated in the northern part of the Norseman-Wiluna belt, 260 km north of Kalgoorlie and 50 km north-northwest of Leonora. The geology of the area has been described by Barnes and others (1974), Thom and Barnes (1977), and by Travis (1975), who also described the mineralization at Marriott prospect. Exploration of the area has been carried out by WMC over the period 1966 to 1976. Outcrop is moderately good.

The Keith-Kilkenny lineament (Williams, 1974) is a major linear disruption zone which strikes north-northwest and passes 10 to 15 km to the east of the Mount Clifford area. Faults branch southwards away from the lineament and enter the area. Easterly striking folds occur to the south near Mount Fouracre; a prominent north-northwest-striking syncline is present to the north at Marshall Pool; and northerly strikes prevail to the west. The intervening Mount Clifford area is therefore triangular; dips in the area are moderate to steep towards directions varying from north to east. The triangular shape is clearly outlined by the chief component of the area which is a pile, up to 1 500 m thick, of metamorphosed picritic to peridotitic flows, stratigraphically and structurally underlain by a thick (1 000 m) lens of coarse-grained olivine peridotite to dunite in the southwestern apex of the triangle. Regional metamorphism of static style has attained greenschist-amphibolite facies transition conditions. Igneous textures are generally excellently preserved in the ultramafic rocks. A similar ultramafic pile occupies the Marshall Pool syncline (McCall and Leishman, 1971) and possibly is a structural repetition of the same sequence (Barnes and others, 1974), although Williams (1976) regarded the Mount Clifford ultramafics as older than the Marshall Pool ultramafics. Tholeiitic metabasalt underlies the Mount Clifford ultramafic pile and poorly exposed felsic metavolcanic rocks underlie and overlie the pile in the northeast and southeast.

Barnes and others (1974) described the Mount Clifford ultramafic pile as occupying an angular asymmetrical syncline plunging at 45 degrees towards the northeast, thus partly accounting for the triangular shape. However, it is also likely that this shape partly reflects a real thickening into the feeder zone of the volcanic pile. Such a proposal is enhanced by the presence of cumulus-type dunitic rocks below the thickest part of the pile, if these rocks are interpreted as a crystal residuum frozen in a subvolcanic magmatic reservoir.

MARRIOTT PROSPECT (28°27′10″S; 120°59′00″E)

This prospect, also known as 832 or Mount Clifford deposit, is 8 km west-northwest of Mount Clifford, a small quartz blow close to abandoned gold workings of the same name. Discovery of a small stringer of nickel gossan, and of sulphide blebs in a nearby outcrop of metaperidotite, was made in 1969 by F. Marriott, a prospector employed by WMC. A gossan sample assayed by Travis and others (1976) contained 2.52 per cent nickel, 1.4 per cent copper, 1 700 ppb palladium and 124 ppb iridium. Using 34 diamond drillholes and a cut-off figure of 0.45 per cent nickel, WMC estimated demonstrated resources to be 723 780 t averaging 1.10 per cent nickel (7 962 t nickel).

The mineralization occurs in a sequence of serpentinized peridotite to olivine peridotite, some 100 to 140 m thick, which dips north at 30 to 35 degrees. This sequence is overlain by two units, each 10 to 30 m thick, of ultramafic tuff and pyritic metasediment separated by massive serpentine-amphibole-chlorite rock about 30 m thick (Travis, 1975). These rocks are succeeded by a pile of numerous, thin (generally 2 to 5 m) flows of picritic to peridotitic composition which face northwards and may attain a thickness of 1 500 m. The flows commonly preserve excellent spinifex and cumulus textures (Barnes and others, 1974). Spinifex textures are not observed in the host peridotite - olivine peridotite sequence, which is dominated by cumulus-textured, serpentinized olivine peridotite, typically composed of 80 to 90 per cent equant olivine pseudomorphs 1 to 3 mm in diameter, surrounded by a chloritic matrix (Travis, 1975). Most mineralization is found in this rock, and only a little occurs in an associated, generally underlying, serpentinized peridotite characterized by skeletal, bladed or dendritic olivine pseudomorphs which are up to several centimetres in length. The matrix of the skeletal peridotite is chlorite and amphibole after acicular to skeletal clinopyroxene (Travis, 1975). Travis proposed that the olivine peridotite was probably intruded into the skeletal peridotite which was likely to be of extrusive origin.

Mineralization averaging more than 1 per cent nickel is confined to an area measuring 180 m (approximately down dip) by 120 m in plan projection. The mineralization evident in outcrop is part of a zone which averages 0.72 per cent nickel. The higher grade mineralization is in several lensoid shoots in the lower part of the olivine peridotite near its contact with the skeletal peridotite. Sulphide-magnetite blebs, a few millimetres in diameter, typify much of the deposit. Veinlets of opaque minerals are also present. Within 100 m of the surface nickel-rich violarite and polydymite are important, but lower down primary assemblages of millerite, godlevskite, heazlewoodite, pentlandite, pyrrhotite and pyrite are found (Travis, 1975). In addition native nickel, native copper, trevorite, chalcopyrite and nickel arsenides are found in the minor mineralization in the skeletal peridotite. The mean Ni:Cu ratio is accordingly very high for the bulk of the mineralization; Travis (1975) reported a value of 400, which is exceptional for a volcanic peridotite-associated deposit.

107 PROSPECT (28°28′45″S; 121°03′20″E)

This prospect is 1.5 km south of Mount Clifford, and was discovered from gossan detected during a routine ironstone sampling programme. Travis and others (1976) analzyed six gossan samples which averaged 922 ppm nickel, 729 ppm copper, 479 ppb palladium and 124 ppb iridium. A lenticular ultramafic body 600 m long and with a downdip dimension of some 240 m, dips steeply to the northeast. The footwall is a metabasalt, and pelitic metasedimentary rocks with chert lenses form the hangingwall. The ultramafic rock consists of serpentinized peridotitic rocks with cumulus and bladed igneous olivine pseudomorphs. Most mineralization occurs at the footwall contact with the metabasalt, and consists of disseminated fine-grained and blebby sulphides and magnetite in granular metaperidotite, with some veinlets in the metabasalt. Pyrite, pyrrhotite and pentlandite are the chief sulphide minerals. The surface expression of the mineralization was tested with 17 percussion drillholes, but significant intersections in drillcore were confined to two diamond drillholes. The best intersection was a drilled width of 0.82 m averaging 3.6 per cent nickel.

OTHER PROSPECTS

TROUGH WELL PROSPECT
(31°40′30″S; 118°48′05″E)

Trough Well prospect is located 70 km north-northwest of Southern Cross on the eastern side of the narrow supracrustal belt extending northwards from that town (Plate 1). In the Bullfinch to Trough Well area this belt consists mainly of moderately exposed metamorphosed tholeiitic eruptive and intrusive rocks, punctuated by linear banded iron-formations and associated poorly exposed, thin ultramafic units. At Trough Well an appendage of north-striking lineated amphibolite, ultramafic rocks and metasedimentary rocks projects eastwards into poorly exposed granitoid rocks. Regional metamorphism attained low- to mid-amphibolite facies conditions (Barrett and others, 1977). In August 1970 gossan was discovered at the southern end of a zone of ultramafic rocks which forms a poorly exposed median strip between flanking areas of lineated amphibolite. Gossan samples averaged 0.97 per cent nickel and 0.12 per cent copper. A sample analyzed by Travis and others (1976) contained 0.49 per cent nickel. 0.07 per cent copper, 244 ppb palladium and 95 ppb iridium. Exploration was carried out by International Mining Corporation in the period 1970 to 1976. Tyrer (1974) provided the most useful description of the geology and mineralization of the area.

The zone of ultramafic rocks has a strike length of some 900 m (north-south) and a width of between 60 and 250 m; granitoid rocks terminate the zone to the north and south. The ultramafic sequence dips steeply westwards and seems to face the same direction. Metamorphosed olivine-rich ultramafic rocks are concentrated at the eastern, presumed basal, contact of the sequence. These rocks are medium- to coarse-grained serpentinites containing some bladed metamorphic olivine pseudomorphs plus talc, anthophyllite and tremolite (Tyrer, 1974). Thinner serpentinites occur higher in the sequence interspersed with dominant tremolite-chlorite rocks, a few of which preserve spinifex textures. A biotite-feldspar-quartz-amphibole schist of possible metasedimentary origin occurs at the base of the ultramafic sequence, especially where overlying nickel mineralization is present (Tyrer, 1974).

Nickel mineralization occurs in three areas along the basal contact of the ultramafic sequence. The best mineralization (the gossan discovery site) is at the southern extremity of the ultramafic zone, where a thin selvedge of amphibolite separates the ultramafic rocks from granitoid intrusions. Drilling of eleven percussion and six diamond drillholes in 1970 to 1971 defined a small shoot 46 m long (north), up to 3 m thick and extending to a vertical depth of 60 m, with an average nickel content of about 2.5 per cent in an estimated 20 000 t of mineralization. Only two of the diamond drillholes (TW 3 and 10) intersected important sulphides. The mineralization is at the base of a serpentinite and it consists entirely of disseminated supergene pyrite and violarite accompanied by chalcopyrite and magnetite. Some 250 m to the north, three diamond drillholes (TW 7, 9 and 11) covering a strike length of 65 m, intersected disseminated pyrrhotite, pentlandite and chalcopyrite, plus magnetite and chromite, in serpentinite. The average grade of this mineralization is about 1.5 per cent nickel and 0.5 per cent copper over a true width of some 1.5 m. A further 250 m to the north, one diamond drillhole (TW 14) intersected 0.52 m of mineralized serpentinite which assayed 1.69 per cent nickel. Three other diamond drillholes in this area failed to encounter significant mineralization.

KOOLYANOBBING PROSPECTS
(31°47′00″S; 119°29′05″E)

The Koolyanobbing supracrustal belt appears to be a large remnant of a northerly branch from the Southern Cross-Forrestania belt (Plate 1). It has a strike length (north-northwest) of some 40 km and is bounded to the southwest by a major mylonitic fault zone. Rock types present in the belt resemble those seen in the Bullfinch - Trough Well area; folded horizons of banded iron-formation occur within tholeiitic and komatiitic metabasalt and amphibolite, with some ultramafic and micaceous metasedimentary rocks. Regional metamorphic grade is low-amphibolite facies. The North Range, north of Koolyanobbing town, is made up of several banded iron-formations which dip at moderate to steep angles towards the northeast, and parallel the western margin of the supracrustal belt. Interlayered with, and to the west of, the banded iron-formations are poorly exposed serpentine-bearing, talc-carbonate and tremolite-chlorite rocks some of which are spinifex-textured. Exploration of the North Range ultramafics was carried out by BHP from 1968 to 1972, and nickeliferous gossans were tested at several sites along the western side of the range. Supergene nickel sulphides were found in the '90 zone' and the '125 zone'. At the 90 zone prospect pyrite, violarite, chalcopyrite, millerite, covellite, and smythite occur as irregular veins and layers parallel to the foliation of talc-carbonate and amphibole-chlorite rocks marginal to the base of a serpentinite (Davis, 1972). The best diamond drillhole intersection averaged 2.92 per cent nickel over a drilled width of 0.61 m. At the 125 zone prospect sulphide intersections occur on the contacts between sulphidic banded iron-formation and ultramafic rocks. Up to 15 cm of breccia sulphides (pyrrhotite, bravoite, chalcopyrite, violarite) are associated with about 1 m of disseminated pyrrhotite, violarite and chalcopyrite (Davis, 1972). The best drillcore intersection averaged 1.75 per cent nickel over a drilled width of 1.22 m.

The nature of the primary nickel sulphide mineralization remains in question. Mineralization at 125 zone prospect may simply result from nickel uptake by sulphidic iron-formation during leaching of the adjacent ultramafic rock.

RUTH WELL PROSPECT (20°52′20″S; 116°52′00″E)

The Ruth Well prospect, discovered by Whim Creek Consolidated NL in 1971, is located in the west Pilbara Block, 30 km west-southwest of Roebourne and 1 800 m southeast of Ruth Well (Fig. 13). The deposit is about 2 km north of the Sholl shear zone, an easterly striking linear dislocation which resembles the tectonic lineaments in the Norseman-Wiluna belt. The local geology consists of a mafic to ultramafic metavolcanic sequence, containing thin metasediments and mafic intrusives, which dips moderately northwards and probably becomes younger in the same direction (Tomich, 1974). Outcrop is fair. According to Tomich, komatiitic metabasalt, spinifex-textured metapicrite to peridotite, tuffaceous metaperidotite, and granular-textured metaperidotite make up the volcanic sequence. The host rock to nickel mineralization contains fine- to medium-grained antigorite plus tremolite, chlorite, talc and carbonate and is peridotitic in composition, being near the top of the ultramafic sequence.

A weak, gossanous, copper-stained surface mineralization has been exposed in a costean, but this appears to have no connection with the sulphides encountered in diamond drillholes which define a shoot about 80 m long (east-west) and 20 m wide in plan projection, plunging eastwards at about 30 degrees. The best intersection is in diamond drillhole 71-RWD-4, which Tomich (1974) has described in detail. At the base of this drillhole, overlying fine-grained serpentinized peridotite, is some 6.5 m (drilled width) of massive magnetite with about 10 per cent interstitial chalcopyrite, pyrrhotite, gersdorffite and niccolite, which assays 0.5 per cent nickel. Above the massive magnetite is "matrix sulphide" about 1.2 m thick containing about 30 per cent chalcopyrite, pyrrhotite and minor violaritized pentlandite interstitial to abundant magnetite euhedra, which averages about 2 per cent nickel and 1 per cent copper. Then follows about 1 m of massive polygonal pyrrhotite and partly violaritized pentlandite which contains 11.5 per cent nickel. A further 2.5 m of "matrix sulphide" succeeds this and is in turn followed by disseminated sulphide in magnetite-rich serpentinite. The whole intersection in 71-RWD-4 averages 3.52 per cent nickel and 0.78 per cent copper over a drilled width of 8.38 m.

Two diamond drillholes collared 75 m to the east and 100 m to the northeast of 71-RWD-4 respectively intersected low-grade disseminated sulphides and thin copper-rich massive-to-matrix sulphides (7.2 per cent nickel and 5.35 per cent copper over 4.6 m) in amphibole-chlorite rocks, at drilled depths of up to 67.5 m.

Though high grade, the deposit is small, probably containing about 70 000 t averaging about 3 per cent nickel at best (2 100 t nickel).

CHAPTER 6

Gabbroid-associated deposits

SUMMARY OF GEOLOGY AND MINERALIZATION

Unlike the intrusive dunite- and volcanic peridotite-associated deposits, the deposits of this type show no marked pattern in their distribution (Fig. 3). Deposits of sufficient size and tenor to be of potential commercial importance are rare in Western Australia; as yet only the deposit at Carr Boyd Rocks has been exploited.

The host intrusions are layered and/or multiple bodies consisting mainly of gabbroidal rocks (gabbronorite in particular) with subordinate pyroxenitic to peridotitic rocks and rare anorthositic rocks concentrated near the base and top respectively. The intrusions may be of tholeiitic affinity, but are differentiated from a basaltic magma. The igneous rocks are typically incompletely recrystallized and altered thus allowing ready identification of primary igneous minerals and order of crystallization (e.g. Williams and Hallberg, 1973). Static igneous textures indicate that alteration was volume for volume which may involve some loss of silica, magnesia and iron in particular, from the ultramafic rocks (Whitfield, 1973).

Mineralized intrusions are small, being less than 100 km^2 in area and irregular to oval in outline. Several intrusions are probably floored and may resemble a sill, laccolith or lopolith in cross section. Evidence for gravity-induced differentiation in the form of phase and cryptic layering is common. The specific host rock to the nickel sulphides may be a gabbro, gabbronorite, pyroxenite, peridotite or olivine peridotite forming either a conformable layer in the intrusion, or, more rarely, forming discordant bodies and pipe-like structures.

The commonest type of mineralization is stratabound, low-grade disseminated or blebby sulphide with rare patches of matrix sulphide and thin veins or lenses of massive sulphide. Bigger bodies of matrix-to-massive sulphide and breccia sulphide (rock fragments in a sulphide matrix) are so far known only from the Carr Boyd Rocks and Sally Malay deposits. In both these deposits the orebodies are steeply plunging or dipping, are broken up by faults and are very variable in thickness. Accordingly, despite the nickel grade of the actual mineralization, the bulk grade as mined is unlikely to exceed 1.75 per cent nickel. The massive, matrix and breccia sulphides are in fact of low tenor, with nickel contents of between 2 and 6 per cent because of high pyrrhotite:pentlandite ratios which are commonly around five to one.

Pyrrhotite dominates all sulphide assemblages and it may account for an important proportion of the sulphide nickel both as minute flame-like exsolution bodies of pentlandite, and as nickel in solid solution. Much pyrrhotite in matrix, breccia and massive sulphides is medium to very coarse grained, anhedral, and lacks deformation textures (such as lanceolate twins or kink bands) or annealing-recrystallization textures. The next most abundant sulphide phase may be pentlandite, chalcopyrite or pyrite. Bulk Ni:Cu ratios are below 7 and decline to less than unity: for Carr Boyd and Sally Malay the ratio is about 3 (Fig. 14). Bulk Ni:Co ratios are about 25, which is significantly lower than other sulphide deposit types. Titaniferous and chromian varieties of magnetite are also present. In disseminated and matrix mineralization, sulphide-silicate grain contacts are typically smooth, rounded and lobate and suggest that the sulphides represent an intercumulus liquid phase to cumulus silicate phases (e.g. pyroxene, olivine, plagioclase). With increasing alteration of the silicate gangue, static metamorphic intergrowth textures between silicates and sulphides are superimposed on this primary magmatic texture.

GENESIS

Many features of the magmatic model of genesis as described in Chapters 4 and 5 are considered equally applicable to gabbroid-associated deposits. The more copper- and cobalt-rich nature of the sulphide assemblages the less magnesian bulk composition of the host intrusions is consistent with the magmatic model (see Chapter 2). Furthermore, within the gabbroid-associated deposits higher Ni:Cu ratios generally correlate with a more magnesian host rock. Preserved intercumulus sulphide textures clearly point to the former existence of immiscible Fe-Ni-Cu sulphide liquids at the magmatic stage. Metamorphic modification does not seem to have been important. Thornett (1981) indicated that salic contamination was important in inducing early separation of a sulphide liquid at Sally Malay.

ARCHAEAN DEPOSITS

YILGARN BLOCK

BULONG COMPLEX NORTH PROSPECT
(30°40′45″S; 121°49′00″E)

The Bulong Complex is a mafic to ultramafic layered intrusion covering an area of some 200 km^2, situated 30 km east of Kalgoorlie (Williams, 1970; Moeskops, 1973). The complex is about 37 km long but has a maximum stratigraphic thickness of only 1 100 m (outcrop width is up to 3 km), and has been emplaced essentially concordantly into felsic metavolcanic or volcaniclastic country rocks. The region has been folded and metamorphosed to the middle greenschist facies; the layering in the complex now dips steeply and is locally overturned. Outcrop is good in the north, and poor in the south where lateritic profiles (some nickeliferous) are developed.

Despite regional metamorphism, igneous textures and some relict igneous minerals are preserved. Several sills, up to 400 m thick, are separated by sheets of country rock. Spinifex-textured basal chilled zones 1 to 3 m thick, are overlain by serpentinized olivine peridotite to dunite (olivine + chromite cumulates) and capped by thin layers of metamorphosed orthopyroxene, orthopyroxene-clinopyroxene and finally plagioclase-clinopyroxene-orthopyroxene cumulate rocks (Moeskops, 1977). In the olivine cumulates the (silicate) nickel content decreases upwards from 3 500 to 1 000 ppm (Moeskops, 1977). The complex has komatiitic affinities.

About 8 km north of Bulong, on the northwestern, east-dipping margin of the complex, weak nickel sulphide mineralization was discovered by Selco in 1968 (Moeskops, 1975). Three of six diamond drillholes encountered sulphides containing up to 0.5 per cent nickel, 0.3 per cent copper and 0.1 per cent cobalt in unlayered serpentinite immediately above a sheet of country rock about 20 m thick. Supergene sulphide minerals predominate, but the primary mineralogy is indicated to be pyrrhotite, pyrite, magnetite, chalcopyrite and sparse pentlandite. The sulphides occur as blebs, 1 to 2 mm in diameter, which Moeskops (1975) regarded as having replaced olivine grains. Subsequent recrystallization of sulphides with metamorphic silicates has occurred.

CARR BOYD ROCKS DEPOSIT (30°04′00″S, 121°37′45″E)

General

The Carr Boyd Rocks deposit is 80 km north-northeast of Kalgoorlie. The deposit is located on the western side of a 75 km^2 metamorphosed layered intrusion of olivine peridotite, harzburgite, bronzitite (orthopyroxenite), troctolite, norite and olivine anorthosite of supposed tholeiitic affinities (Purvis and others, 1972). In 1968 Great Boulder, in joint venture with North Kalgurli, began exploring the sites of aeromagnetic anomalies in the area. Geological mapping and soil geochemical sampling was conducted on grid lines oriented northeast and set 122 m apart. Mafic rocks coloured with copper and nickel carbonate stainings were found, which assayed 0.57 per cent nickel and 0.55 per cent copper (Schultz, 1975). Costeans were excavated and gossanous ultramafic rocks containing up to 1.75 per cent nickel and 0.50 per cent copper were discovered. Beginning in 1969, 107 diamond drillholes were drilled to evaluate the anomalous area and indicated resources of 1.361 Mt averaging 1.65 per cent nickel (22 456 t nickel) and 0.57 per cent copper were outlined in three shoots numbered 1, 2 and 3.

Development of No 1 shoot by glory hole and shaft sinking to gain access to deeper ore took place in 1971-1972, but the lack of a suitable sales contract obliged the operators to put the mine on a care and maintenance basis in September 1972. A contract was signed with WMC in June 1973 and limited production began in July. The ore reserves had been significantly reduced by now (Table 3) because (i) underground development had shown the shoots to be smaller than interpreted from surface drilling; and (ii) low grade ore blocks were deleted from the reserves because of adverse changes in mining costs and the nickel market. Production continued until June 1975 with average head grades being 1.44 per cent nickel and 0.46 per cent copper.

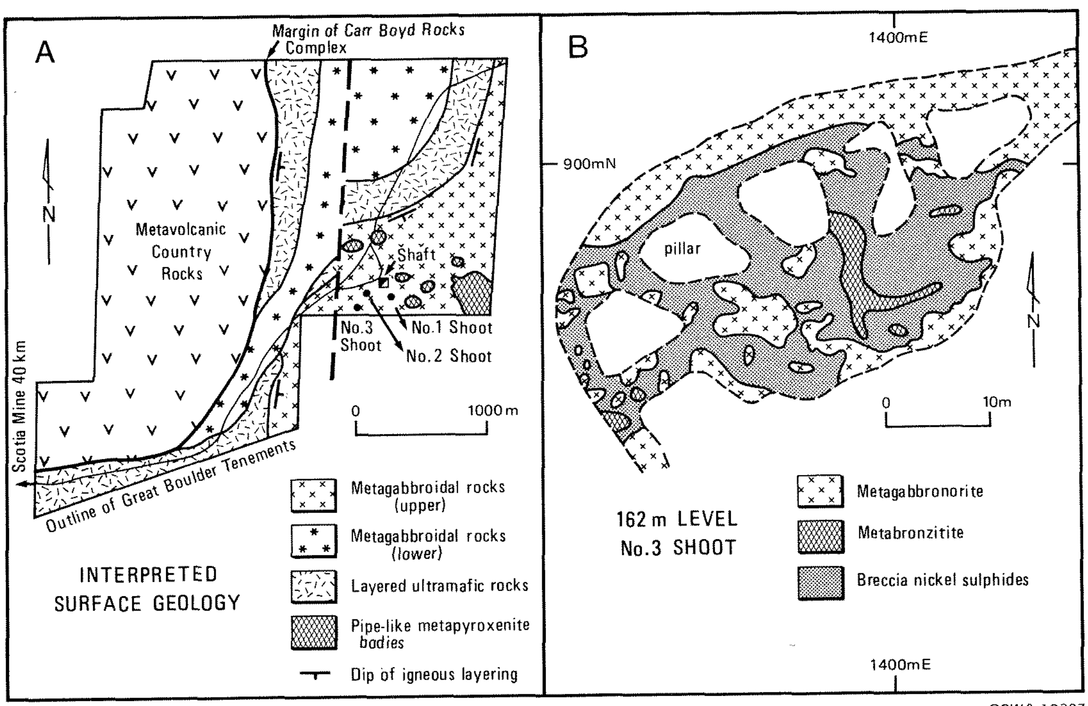


Figure 81. A — Interpreted surface geology (from Purvis and others, 1972). B — detailed geology of No 3 shoot at 162 m level.

Mining was carried out by long-hole open stoping, but poor fragmentation of ore slowed production which was from three levels at 61 m, 107 m and 162 m with a shaft sunk to 211 m. It was discovered that No 2 shoot did not persist below the 162 m level. This discovery, combined with increased costs, low productivity and a lack of underground development, led to closure in mid-1975. Ownership of the mine passed to WMC in February 1976 and production briefly resumed in June 1977 before final closure in September 1977. At this time remaining demonstrated plus inferred resources to a vertical depth of 300 m were estimated at 547 774 t averaging 1.53 per cent nickel (8 381 t nickel) and 0.49 per cent copper for a cut-off figure of 1 per cent nickel. Some 70 per cent of this resource is below the 162 m level.

Geology

The central, and well exposed, part of the layered intrusion, named the Carr Boyd Rocks complex by Purvis and others (1972), consists of medium- to coarse-grained, layered metagabbroids with some ultramafic units. The gabbroid rocks dip inwards towards the centre of the complex and are underlain by poorly exposed, layered

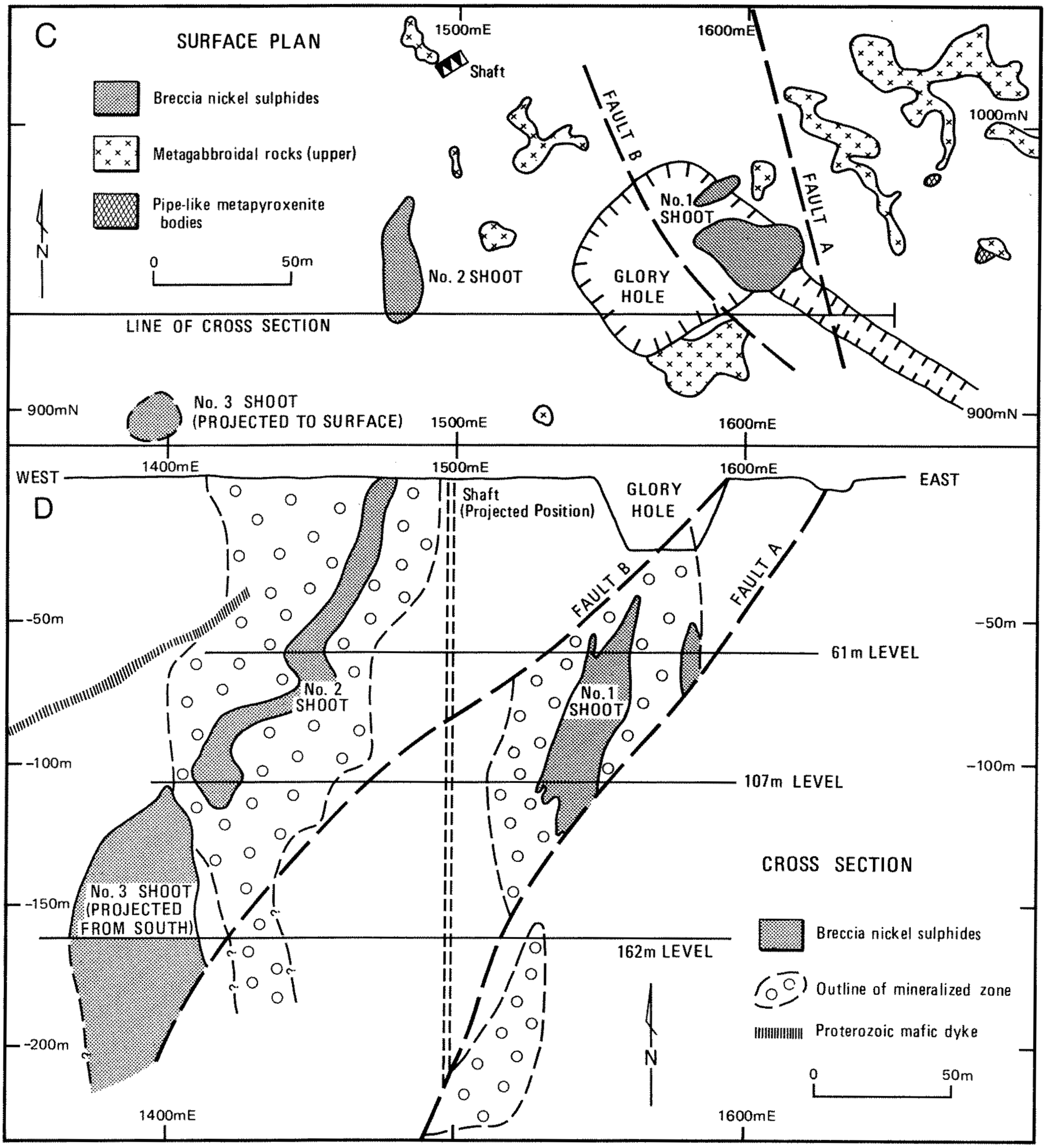


Figure 81. C — surface plan. D — cross section. Carr Boyd Rocks deposit (data are from Great Boulder Mines Ltd).

ultramafic rocks. The complex intrudes north-striking supracrustal rocks, but is itself intruded in the north by granitoid rocks. The igneous layering dips towards the southeast in the vicinity of the deposit, where Purvis and others (1972) recognized two major groups of ultramafic to mafic igneous units attaining an aggregate thickness of up to 3 000 m. In both groups cyclically layered bronzitite, olivine peridotite and harzburgite are prominent in the lower unit(s) and olivine norite, gabbronorite and some olivine-plagioclase-bearing varieties are prominent in the upper unit. Metamorphic mineralogy now prevails, with serpentine, tremolite-actinolite, anthophyllite, cummingtonite, talc and chlorite incompletely replacing the igneous minerals. Dykes of gabbronorite and veins or pipe-like bodies of pyroxenite intrude the layered rocks.

Mineralization

The nickel-copper sulphide mineralization is associated with cross-cutting, steeply included pipe-like bodies and vein stockworks of medium — to very coarse-grained bronzitite, now altered to rocks containing anthophyllite, tremolite-actinolite, talc, chlorite and plagioclase with some relict igneous pyroxene. These bodies occur in an east-northeast-striking zone about 800 m wide in the uppermost gabbroidal unit of the complex (Fig. 81). The three known mineralized bodies are relatively small and consist of a central zone (denoted as shoots on Fig. 81) of breccia sulphides and high-grade disseminated sulphides averaging more than 1 per cent nickel, and an enveloping mineralized zone comprising veins of bronzitite in gabbronorite with patchy disseminated sulphides and veinlets developed mainly in the bronzitite.

The three ore shoots plunge steeply west and are displaced by west-dipping faults (Fig. 81). The Number 3 shoot is blind, and averages 1.72 per cent nickel and 0.45 per cent copper. The Numbers 1 and 2 shoots average 1.41 per cent nickel and 0.50 per cent copper. The average composition of the shoots by volume is as follows (Schultz, 1975):

70 per cent:	silicate inclusions (bronzitite, lesser gabbronorite or individual constituent crystals of these rocks)
20 per cent	nickeliferous (0.5 per cent) monoclinic pyrrhotite
4 per cent:	pentlandite
2 per cent:	chalcopyrite
2 per cent:	pyrite
2 per cent:	chrome-titanomagnetite

The silicate inclusions range in size from individual crystals to irregular blocks up to 10 m in diameter (Fig. 81).

The sulphide matrix to the large, barren silicate inclusions may be disseminated, matrix or massive ore. Foliation or mineralogical layering is absent. The pyrrhotite is medium to very coarse grained (some up to 25 mm in diameter), cleaved in some samples, and is irregular in outline with little internal deformation being evident. Exsolved pentlandite occurs as flames in the pyrrhotite. In matrix ore a single pyrrhotite grain may enclose many bronzites or bronzite pseudomorphs. Pentlandite is finer grained and well cleaved and tends to occur along pyrrhotite-pyrrhotite or pyrrhotite-gangue contacts. Pyrite is fine to medium grained and subhedral to euhedral, and may be intergrown with chalcopyrite. Chalcopyrite is erratically distributed and tends to occur in local segregations of coarse- to very coarse-grained (200 mm in diameter) anhedral crystals, in places almost to the total exclusion of other sulphide phases.

Textural relationships between silicates and sulphides depend on the degree of metamorphic alteration which affects the silicates. Where the bronzite is fresh or merely rimmed by anthophyllite or talc, the bronzite prisms are distinctly rounded and consequently the sulphide aggregates are lobate in outline (Fig. 95C). This texture is regarded as magmatic, with the sulphides representing an intercumulus liquid phase to the cumulus bronzite crystals. With increasing hydration of the bronzite static metamorphic intergrowth textures between amphiboles and sulphides become increasingly superimposed on the magmatic texture, but the blurred outlines of bronzite pseudomorphs can still be discerned (Fig. 95D). Some matrix ore does grade into breccia ore consisting of small fragmented crystals of metamorphic silicate minerals, which is a fine-scale analogue of the coarse breccia texture of the shoots as a whole.

Massive sulphides average about 6 per cent nickel and 2 per cent copper (Purvis and others, 1972), and matrix sulphides contain up to 4 per cent nickel. The bulk Ni:Cu ratio of the deposit is 3.09. The Ni:Co ratio is about 30.

The No 3 shoot and the associated low-grade mineralized zone below No 2 shoot are both open at depth, where they pass into tenements originally held by Pacminex and Carr Boyd Minerals. Other geochemical and geophysical anomalies detected from surface surveys in the area remain to be properly tested.

HERON WELL PROSPECT (29°06′00″S, 121°22′30″E)

Heron Well prospect is 75 km north-northeast of Menzies, close to the Menzies-Leonora road and east of Heron Well. Metamorphosed gabbroid and dolerite occur in small intrusions emplaced in felsic and mafic metavolcanic rocks and quartz porphyries. Exploration by Glomex and Le Nickel in the early 1970s encountered weak mineralization about 2m wide and 100 m long at 100 m drilled depth, the best drill intersection being a 2 m width averaging 1.32 per cent nickel and 1.12 per cent copper. The mineralization occurs in a steeply east-dipping contact zone between tremolitic rocks marginal to a mafic-ultramafic intrusive, and felsic metavolcanic rocks.

MOUNT VENN PROSPECT (28°06′20″S; 123°30′25″E)

At Mount Venn, 350 km northeast of Kalgoorlie, weak nickel-copper mineralization has been found in a small layered intrusion emplaced into felsic metavolcanic rocks but which is itself intruded by granitoid rocks. The intrusion is metamorphosed and folded into a south-plunging syncline so that meta-pyroxenites predominate in the north and metagabbroids occupying higher stratigraphic levels are abundant in the south (Gower and Boegli, 1977).

Gossanous and copper-stained shows in coarse-grained metapyroxenite assaying up to 0.8 per cent nickel and 1 per cent copper in an area 3 km south of Mount Venn were investigated by Tasminex and Tin Creek Mining in 1970-1972. Two gossans analyzed by Travis and others (1976) contained 0.34 per cent nickel and 0.09 per cent copper and low palladium and iridium. Two diamond drillholes completed to test the surface anomalies encountered patchy, disseminated to massive pyrrhotite with minor chalcopyrite in metapyroxenite and metagabbro. The pyrrhotite is nickeliferous and contains exsolution lamellae of pentlandite. Despite some wildly optimistic statements concerning the prospect's potential, the best nickel intersection was a drilled width of 0.3 m averaging 0.44 per cent nickel, immediately above a 1.2 m width averaging 1.5 per cent copper in diamond drillhole TDH 3.

NEW NORCIA PROSPECT (31°05′50″S, 116°15′50″E)

The New Norcia prospect is located 15 km south-southeast of New Norcia and 17 km west of Calingiri in an area of partly cleared woodland with little topographic relief. Outcrop is poor and lateritic cappings are extensive. Tenements were taken out over the area by Otter in August 1975 following reconnaissance sampling. Subsequent surface geochemical sampling programmes indicated the presence of anomalous amounts of copper and nickel associated with metapyroxenitic rocks mainly in an area some 800 m long, oriented north-northwest. Shell entered into joint venture with Otter in March 1977 and carried out detailed exploration including ground and airborne magnetic surveys, geological mapping, intensive rotary air-blast geochemical drilling (16 375 m total) and the completion of 13 percussion and 6 diamond drillholes.

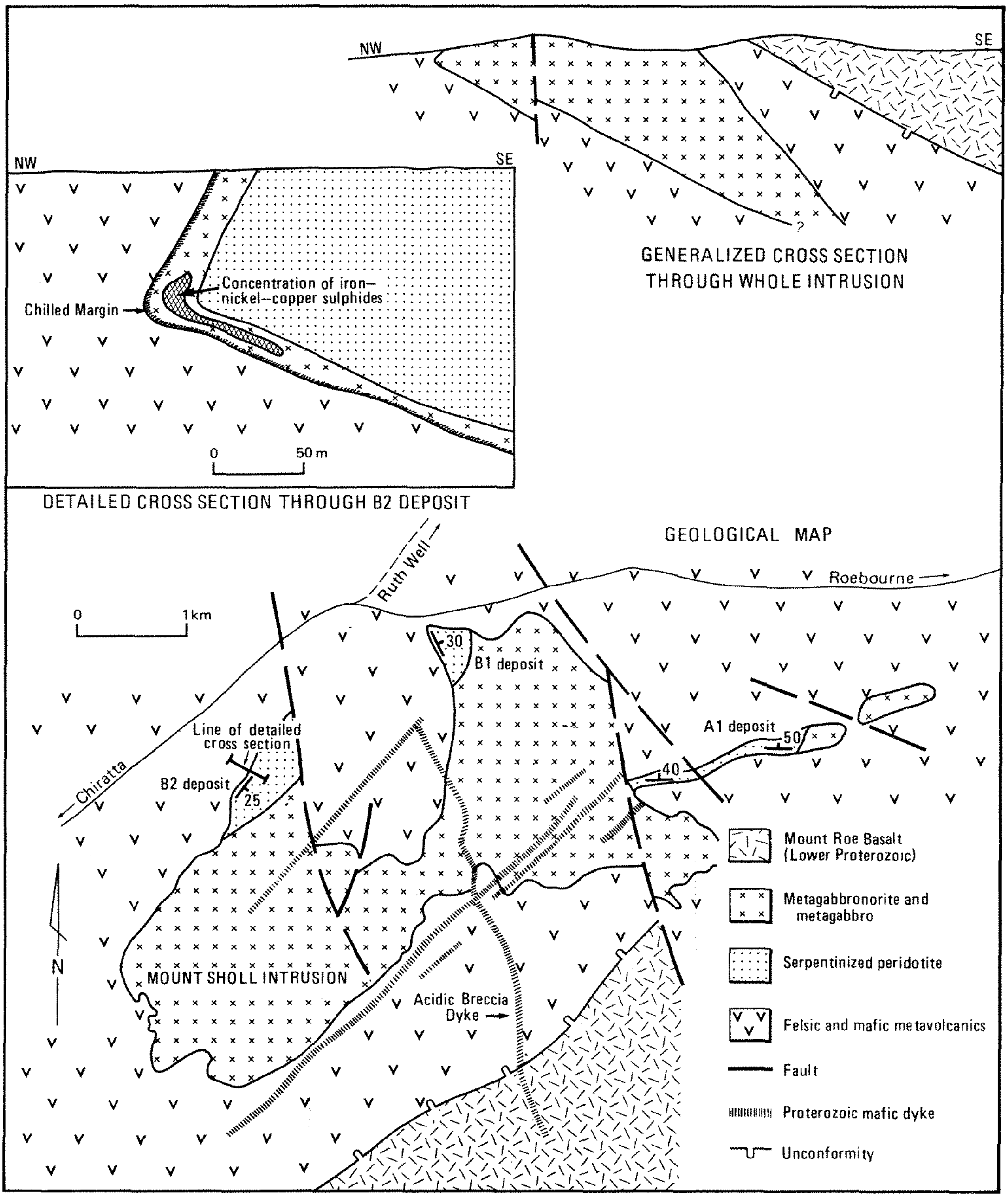


Figure 82. Geological map, generalized cross section and detailed cross section of the Mount Sholl deposit (data from Westfield Minerals (WA) NL).

Medium- to coarse-grained tremolite-actinolite rock (metapyroxenite) is accompanied by metadolerite-gabbro, probably mainly in cross-cutting north-striking dykes, and small lenses of serpentinite and medium- to coarse-grained serpentine-tremolite rocks. Quartz-feldspar schist and amphibolite are also present and may represent the country rocks. The diamond drillholes intersected patches of disseminated, matrix and massive sulphides occurring in the metapyroxenite and serpentine-tremolite rocks, which seem to be part of an intrusive complex. Pyrrhotite is the dominant sulphide and is accompanied by lesser chalcopyrite, minor pyrite and rare pentlandite. The best intersections are only in the range of 0.2 to 0.4 m containing up to 1.5 cent nickel and similar amounts of copper.

YOUANGARRA AREA PROSPECTS (28°48′30″S, 118°45′00″E)

These prospects occur in an area 6 to 9 km southwest of Youangarra homestead, and between Curran Well in the east and Cooliboo Bore in the west. A poorly exposed complex of metamorphosed gabbroid and dolerite with subordinate pyroxenite, peridotite and anorthosite occupies an area of about 100 km^2 extending northwards to the Freddie Well zinc deposit. Large inclusions and rafts of recrystallized banded iron-formation, chert, (quartzite), and other metasediments are present within the complex. Felsic dykes and plutonic granitoids intrude the complex.

Geological mapping, ironstone and soil geochemical surveys (principally by WMC) from 1972 to 1976 located gossanous metagabbronorite and pyroxenite containing anomalous amounts of nickel and copper in occurrences 2 to 4 km west of Curran Well. Percussion and limited diamond drilling related these anomalies to isolated patches of disseminated and rare matrix-to-breccia sulphides. The disseminated-to-matrix sulphides have a lobate outline and seem to represent an intercumulus phase to pyroxene. The sulphides are dominantly coarse-grained pyrrhotite and fine- to medium-grained pyrite, minor chalcopyrite, and accessory pentlandite/violarite mainly as exsolution lamellae in pyrrhotite. The best nickel intersection in WMC drillcore was 1.22 m averaging 2.2 per cent nickel and 0.14 per cent copper in drillhole MYOD 44. This corresponds to a section of pyritic, magnetite-rich breccia sulphide.

Roebourne Exploration, in joint venture with Australian Ores and Minerals and Kralco, discovered similar mineralization just south of ground explored by WMC (TR 3930), located in an area 3.7 km west-southwest of Curran Well. Costeans exposed weathered metagabbro with weak iron-oxide staining and some recrystallized banded iron-formation remnants. Percussion and diamond drilling encountered disseminated, matrix and massive iron-copper-nickel sulphides in metagabbro cut by faults. The best intersection in diamond drillcore appears to have been a drilled length of 10 m averaging 1.34 per cent nickel and 0.71 per cent copper (DDH 2).

PILBARA BLOCK

MOUNT SHOLL DEPOSITS (20°55′10″S, 116°53′10″E)

The Mount Sholl deposits occur at three localities on the northern side of a metamorphosed mafic to ultramafic intrusion 23 km south of Karratha. Mount Sholl itself is a high point at the northern end of an outlier of Lower Proterozoic Mount Roe Basalt immediately south of the intrusion. The intrusion is irregular in outline forming an outcrop some 6 km long and up to 3 km wide, with a long axis oriented parallel to northeast-striking mafic to felsic metavolcanic country rocks (Fig. 82). The Sholl shear zone (see Chapter 3) is a major tectonic lineament occurring 1 km to the north. Sets of faults trending northwest and northeast complicate the geometry of the intrusion, but C.I. Mathison (pers. comm., 1979) has interpreted the intrusion to be a wedge-shaped laccolith-like body tilted southeastwards by post - Lower Proterozoic movements (Fig. 82).

The bulk of the intrusion consists of monotonous, unlayered metagabbronorite and metagabbro which may form bold hilly terrain. A thin margin of low-lying, poorly exposed or concealed serpentinized peridotite occurs in the northwest (B1 and B2 deposits), and a thin, sill-like tongue of gabbro and peridotite extends 3 km east-northeastwards from the main intrusion (A1 deposit) as shown in Figure 82. This geological information stems from exploration carried out by Westfield in the early 1970s. A gossan sample from A1 deposit contained 0.56 per cent nickel, 4.55 per cent copper, 354 ppb palladium and 217 ppb iridium (Travis and others, 1976).

Diamond drilling by Westfield has demonstrated that although the mineralization occurs in three localities, each containing ultramafic intrusive rocks, the sulphides are commonly concentrated in a thin marginal zone of gabbroidal rock (detailed cross section, Fig. 82). Furthermore, at the B1 and B2 deposits this concentration is in the apex of the wedge-like margin of the intrusion. It is not clear whether this wedge-like feature is wholly primary or partly the result of deformation.

The bulk of the mineralization is in the B2 deposit and has no surface expression. Chalcopyrite, pyrrhotite and pentlandite are the main sulphide minerals which occur as lobate aggregates with static metamorphic textures indicating marginal intergrowth with secondary silicate minerals. The texture of the sulphide aggregates is regarded as that of a modified intercumulus sulphide liquid. Some of the better drillcore intersections are 16.8 m averaging 1.31 per cent nickel and 1.38 per cent copper; and 4.6 m averaging 0.38 per cent nickel and 0.62 per cent copper. Published indicated resources are about 4.04 Mt of 0.6 per cent copper and 0.5 per cent nickel using a 0.5 per cent nickel plus copper cut-off figure.

RADIO HILL PROSPECT (20°59′40″S; 116°52′10″E)

Radio Hill prospect is 30 km south of Karratha, 8 km southwest of Mount Sholl and 1 km west of the Dampier — Tom Price railway. The geological setting is similar to that of the intrusion at Mount Sholl, but the Radio Hill intrusion is a smaller body, about 5 km^2 in area, which Richardson (1976) interpreted as a lopolith, slightly tilted towards the north. This results in the successive outcrop (or subcrop) from north to south of metamorphosed granophyre, granophyric diorite, laminated felsic gabbroid, mafic gabbroid, pyroxenite and peridotite of tholeiitic affinities (Richardson, 1976). The ultramafic rocks are not exposed but have been encountered in exploratory diamond drilling (3 drillholes) undertaken by Westfield. The total stratigraphic thickness of the intrusion is at least 800 m.

Patchy blebs of medium-grained, disseminated-to matrix sulphides and fine-grained disseminations of sulphides are concentrated in basal peridotite and olivine pyroxenite. Accessory sulphides do occur in the mafic and felsic layered rocks but chalcopyrite is the only important phase. Pyrrhotite, with subordinate pentlandite and chalcopyrite, form lobate, intercumulus aggregates of up to 12 per cent (by volume) in the ultramafic rocks. A layer of pyrrhotite-rich massive sulphide 20 cm thick, occurs 8 m above the basal contact of the intrusion with statically recrystallized metabasalt in diamond drillhole RHD 2. The nickel content of the sulphide fraction is low; Richardson (1976) obtained contents of 0.39 and 0.74 per cent nickel and 0.82 and 0.33 per cent copper respectively for two disseminated-matrix sulphide samples.

OTHER OCCURRENCES

The Munni Munni Complex (21°07′40″S; 116°50′10″E) is a layered sequence of little altered clinopyroxenite, peridotite and gabbroid of tholeiitic affinities, situated 48 km southwest of Roebourne

(Donaldson, 1974). Minor amounts of chalcopyrite, pyrrhotite and pentlandite occur in altered clinopyroxenite which forms a thin marginal zone to the complex. Donaldson (1974) reported that drilling (by Westfield) had intersected disseminated and a little massive nickel-copper sulphide on the basal contact of the intrusion.

Some 8 km west-southwest of Roebourne, and 1.5 km east-southeast of the Carlow Castle copper-gold workings (20°48′20″S; 117°03′40″E), diamond drilling by Amax encountered minor amounts of iron-nickel-copper sulphides in a layered mafic-ultramafic complex. Pyrrhotite, the dominant sulphide, was found in serpentinized pyroxenites. A lens of massive sulphides 5 cm thick intersected in one drillhole averaged 0.95 per cent nickel and 0.43 per cent copper over 0.3 m of core assayed.

Differentiated sills and layered intrusions in the Soanesville area 70 km west-southwest of Marble Bar are described by McCall (1971) and Hickman (in press). Rock compositions represented include altered olivine peridotite, clinopyroxenite, websterite, gabbronorite, diorite and anorthosite. The country rocks are chert, banded iron-formation, clastic metasediments and metabasaltic rocks. The intrusions are more-or-less concordant and have been folded along with the country rocks. Exploration of tenements (21°29′20″S; 119°09′50″E) in dissected terrain situated 10 km west of Dalton Mining Centre by Kingsway in 1970-1971, resulted in the discovery of nickel sulphides at the basal (eastern) contact of a serpentinized peridotite with chert (in turn underlain by metagabbroid). Eleven diamond drillholes intersected low-grade disseminated sulphides and two adjacent drillholes intersected narrow widths (0.4 m) of high-tenor massive sulphides (20 to 26 per cent nickel). Including overlying low-grade sulphides, average intersections for two drillholes were 3.50 m at 2.55 per cent nickel and 1.16 per cent copper (DDH 3) and 3.66 m at 2.41 per cent nickel and 0.61 per cent copper (DDH 5).

PROTEROZOIC DEPOSITS

JIMBERLANA DYKE

GEOLOGY

The Jimberlana Dyke is the largest member of a suite of east to east-northeast-striking, early Proterozoic mafic dykes which transect the eastern Yilgarn Block and are named the Widgiemooltha Dyke Suite (Sofoulis, 1966). The dyke is some 200 km long and up to 2.5 km wide and has igneous layering and petrology resembling that of the Great Dyke in Zimbabwe (Campbell and others, 1970). The Jimberlana Dyke has komatiitic affinities (McCall, 1973). The dyke is thickest in the east, in the vicinity of Norseman, where canoe-shaped layered mafic to ultramafic complexes occur in five localities. Marginal to and underlying these complexes, and forming the dyke along strike in between them, are steeply dipping gabbronorite, feldspathic bronzitite, and in places a central olivine-bearing ultramafic zone, which indicate a "reversed" fractionation trend perhaps caused by flow differentiation (Travis, 1975a).

MINERALIZATION

From 1966 to 1972, WMC in joint venture with Central Norseman, explored a 90 km length of the dyke in the Norseman region. Many nickel-copper sulphide occurrences were located, mainly using soil geochemical surveys, but none tested was of sufficient size or grade to be of economic importance (Travis, 1975a). Low-grade, fine-grained, disseminated iron-nickel-copper sulphides in gabbronorite marginal to the dyke were located at five prospects named Bronzite Ridge (32°10′20″S; 121°16′50″E), Spinifex (32°08′00″S; 121°41′05″E), Cowan North (32°09′00″S; 121°43′10″E), Cowan South (32°09′50″S; 121°43′00″E) and Dundas Hills (32°08′10″; 121°53′05″E) from west to east (Plate 1). These prospects occur where the marginal rocks of the dyke taper to a thin selvedge below the layered rocks of canoe-shaped complexes (Travis, 1975a). Pyrrhotite, pyrite, pentlandite and chalcopyrite are the sulphide phases present; combined nickel and copper assays are generally less than 0.5 per cent. At Cowan South prospect, 6 km northwest of Norseman, a discontinuous layer of massive sulphide, up to 0.3 m thick, lies beneath disseminated sulphides and in contact with hornfelsed metabasalt to the south. At Bronzite Ridge prospect, 47 km west of Norseman, a smaller lenticular satellite intrusion of gabbronorite contains disseminated and veinlet supergene sulphides which average more than 1.5 per cent nickel plus copper in a pipe-like zone traced down a 30 degrees westward plunge for 70 m. Two gossan samples from Bronzite Ridge analyzed by Travis and others (1976) contained 1.1 per cent nickel, 0.38 per cent copper, 1 768 ppb palladium and 91 ppb iridium.

Some exploration was done for precious metals and chromite but only low contents were encountered (Travis, 1975).

HALLS CREEK PROVINCE

CORKWOOD PROSPECT (17°20′00″S; 128°10′40″E)

Corkwood prospect is 115 km north-northeast of Halls Creek and 14 km east of the Great Northern Highway. The prospect is in a north-northeast-striking narrow zone of high-grade metamorphic rocks bounded by the Halls Creek Fault to the east and the Mabel Downs Granodiorite to the west. Mineralization is associated with a narrow, steeply inclined lens of amphibolite and mafic granulite, some 2 500 m long and up to 250 m wide, enclosed in layered quartz-feldspar-biotite-garnet gneiss (Nevill, 1974; Wilding, 1980). Outcrop is good and plentiful.

In 1972 Anglo American discovered linear, patchy gossanous material, assaying up to 1 per cent nickel, in zones up to 220 m long and 5 m wide (Wilding, 1980). Diamond drilling in 1973 in the northern half of the lens encountered, at shallow depths, massive veins and disseminations of pyrrhotite, pyrite, pentlandite/violarite, and chalcopyrite in mafic granulite enveloped by amphibolite. The grade of this mineralization varied from 0.3 to 2.6 per cent nickel, 0.1 to 0.5 per cent copper and 0.02 to 0.1 per cent cobalt over true widths of 1.5 to 4 m. The higher grades occurred over the narrower widths.

KELLER CREEK PROSPECT (17°18′44″S; 127°57′30″E)

Keller Creek prospect is to the west of the Mabel Downs Granodiorite, 21 km southwest of Mabel Downs homestead and 9.5 km west of the Great Northern Highway. Exploration by BHP in 1973 to 1975 outlined a small lens (less than 100 m long) of low-grade, disseminated pyrrhotite, chalcopyrite and pentlandite in gabbroidal rocks which have intruded east-striking felsic gneiss (Tickalara Metamorphics). Some mineralization occurs in a quartz monzonite stock which has intruded the gabbroid and the gneiss. The best diamond drillhole intersection of 7.8 m averaging 1.01 per cent nickel and 0.26 per cent copper occurred in this stock.

SALLY MALAY DEPOSIT (17°21′10″S; 128°01′20″E)

General

Sally Malay deposit is 3.7 km north of Dave Hill and 2.5 km west of the Great Northern Highway in hilly, dissected terrain west of the Mabel Downs Granodiorite. The deposit was discovered in 1974 by Anglo American during investigation of geochemical anomalies (maximum 195 ppm nickel, 100 ppm copper) found during a stream

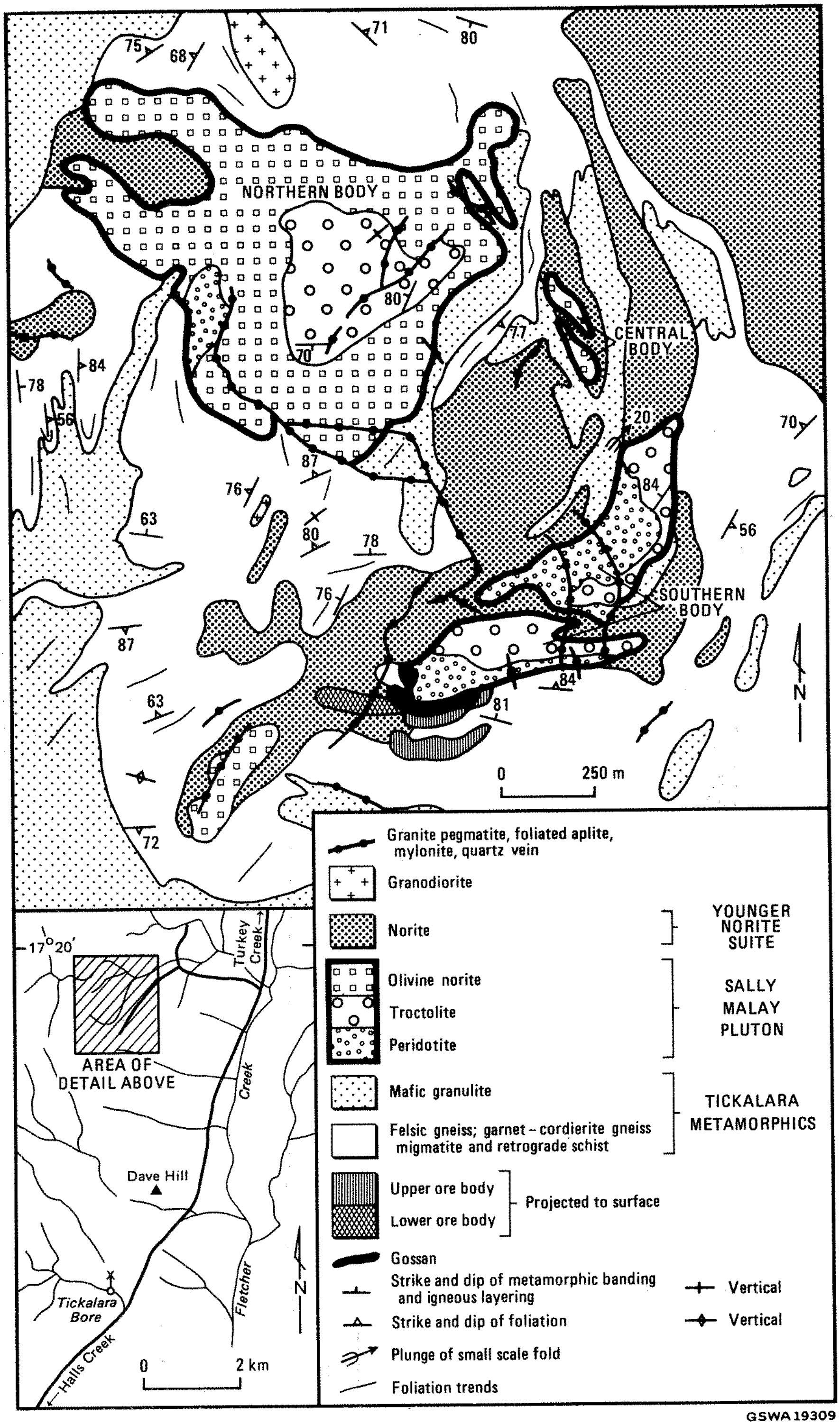


Figure 83. Geological map of the Sally Malay area based on mapping by J.R. Thornett and data from Australian Anglo American Limited.

sediment geochemical survey. Samples of the prominent gossan found occurring on the slope above the creek returned assays of up to 2.1 per cent nickel and 1.4 per cent copper. The main gossan is an arcuate body about 250 m long and up to 35 m wide. Six inclined diamond drillholes were sited to test the gossan at depth, and the three collared on the southwestern side of the gossan intersected massive and disseminated nickel sulphides. The best intersection was a drilled width of 9.5 m averaging 2.39 per cent nickel and 1.14 per cent copper (DDH 8). A further 15 diamond drillholes were completed in 1975 and 8 of these intersected massive nickel sulphides; the best intersection was a true width of 12 m averaging 2.97 per cent nickel and 0.91 per copper. Evaluation diamond drilling continued in 1977-1978 and when the programme ended in December some 95 drillholes (and deflections from existing drillholes) had been bored, totalling about 26 400 m, with the deepest drillhole reaching a vertical depth of 945 m. Probable and possible resources respectively were estimated by Anglo American at 3.4 Mt averaging 2.12 per cent nickel (72 080 t nickel) 0.79 per cent copper and 0.11 per cent cobalt; and 3.8 Mt with an average grade greater than 2 per cent nickel.

Geology

The deposit occurs in a small pluton of little-altered mafic to ultramafic intrusive rocks assigned to the McIntosh Gabbro (Dow and Gemuts, 1967). The McIntosh Gabbro suite has intruded complexly deformed, high-grade (mid-amphibolite to granulite facies) felsic gneiss, with subordinate mafic granulite and amphibolite of the Tickalara Metamorphics (Fig. 83). Layered quartz-feldspar-(mainly microcline) biotite-garnet gneiss, containing mobilized and nebulitic areas, convolute folds, boudins and pegmatitic or quartzose segregations, is the dominant country rock and is probably of sedimentary origin (Gemuts, 1971). Andalusite, sillimanite and cordierite occur locally.

The presence of reaction coronas in the gneiss at the contact of the pluton, and the results of two-pyroxene thermometry in mafic granulites, the marginal norite and the peridotite of the pluton, indicate that emplacement of the pluton followed the peak of regional metamorphism (Thornett, 1981). The pluton consists of three separate bodies which have a total surface area of some 2 km^2 (Fig. 83). The southern body consists of harzburgite to lherzolite overlain by troctolite and olivine norite; this sequence is repeated after passing through a second troctolite-harzburgite unit (Thornett, 1981). The central body consists mainly of norite, whereas the northern body is largely norite and troctolite with some gabbro near the top. Rhythmic layering is present mainly in the troctolites, but the norites commonly have an igneous foliation. These planar structures are vertical or dip northwest, and, together with the inferred facing and cryptic variation in olivine, indicate that the pluton was tilted towards the northwest (Thornett, 1981).

Primary igneous textures and mineralogies are generally well preserved but some deformed zones contain granoblastic annealing-recrystallization textures, and some secondary amphiboles and dark micas may be present. In the presence of sulphides, biotite, perthitic microcline, almandine and sodic plagioclase are common phases concentrated at sulphide-silicate grain contacts (Thornett, 1981).

The younger norite suite transgresses the Sally Malay pluton (Fig. 83). The general outcrop pattern and the strike of the commonly subvertical foliations in the gneiss suggest that folding has occurred along easterly and north-northwesterly striking axes. Some open folding has probably involved the Sally Malay pluton, although the competent nature of the rocks appears to have inhibited the development of penetrative tectonic structures in the pluton.

Mineralization

The Sally Malay gossan occurs on an east-striking contact between felsic gneiss to the south and thin, marginal norite overlain by peridotite to the north, and on a closely associated north-dipping fault. The deposit is divisible into upper and lower orebodies (Fig. 83). The upper orebody is represented at the surface by the discovery gossan, but 15 to 20 m below the gossan it consists largely of primary sulphides. This orebody has a strike length of 250 m, a plunge (steeply westwards) length of 550 m, and a vertical extent of 470 m. Although the gossan dips steeply northwards this reverses to a south dip at depth. A low-angle, north-dipping reverse fault divides the upper orebody into two sections by displacing the lower part to the south (Fig. 83). The southern limit of the upper orebody is faulted and the mineralized contact zone is displaced northwards to form the vertical or steeply south-dipping lower orebody, which extends from a vertical depth of 600 to 850 m. Further low-angle reverse faults break up this small orebody.

Important mineralization is closely associated with the peridotite – felsic gneiss contact zone; this contact projects underneath the large mass of younger norite which truncates the peridotite and troctolite to the west at the surface, and is intersected by drilling into the lower orebody. A persistent feature of the mineralized contact zone is the presence of a thin (5 to 30 m) unit of ophitic norite capped by a 1 m-thick unit of picrite, occurring below the basal peridotite. Coarse-grained, massive and breccia sulphides account for the bulk of the mineralization. Fragments of gneiss, gabbronorite, peridotite, and individual crystals of these rocks occur in the breccia sulphides, but the type of fragment commonly relates to the immediate host rock. Pyrrhotite is the major sulphide phase, which lacks deformation textures and contains minute flame-like exsolution bodies of pentlandite. Larger, separate pentlandite grains are also present and chalcopyrite is the remaining sulphide; these two phases constitute up to 20 per cent of the total sulphide assemblage. Some disseminated to matrix sulphide occurs in the marginal ophitic norite where sulphide-silicate contacts are smooth, lobate and of a magmatic intercumulus appearance. Titaniferous and chrome magnetite are minor opaque phases.

ALBANY-FRASER PROVINCE

Known nickel occurrences are confined to small irregular intrusions of deformed and metamorphosed gabbronorite, pyroxenite and peridotite emplaced in the southern end of the Fraser Complex mafic granulites at Gnama South (32°12′10″S, 122°41′10″E) and Talbot (32°16′00″S, 122 °43′00″E).

Exploration was carried out in 1965-1970 by Newmont, based on a proposed analogy with the Thompson nickel belt in Manitoba, Canada (Tyrwhitt and Orridge, 1975). The mineralization at the two occurrences mentioned was found close to gabbronorite-peridotite contacts. Pyrrhotite and subordinate chalcopyrite and pentlandite occur as disseminations, stringers, veinlets, fracture coatings and rare coarse patches, constituting up to 15 per cent sulphides by volume. The best diamond drillhole intersection was at Gnama South where a drilled width of 6 m averaged 0.44 per cent nickel and 0.12 per cent copper. Tyrwhitt and Orridge (1975) suggested that originally magmatic sulphides have been locally redistributed and concentrated during deformation.

CHAPTER 7

Layered sedimentary-associated deposits

SUMMARY AND GENESIS

Disseminated to matrix nickel sulphides occurring as laterally extensive stratiform layers in bedded metasedimentary rocks of unusual composition are the hallmark of this type of deposit. With only three deposits assigned to this type it is unwise to attempt much generalization. Two deposits (Cruickshank, F shoot Windarra) are found in mafic to ultramafic sequences in a setting which is identical to volcanic peridotite-associated deposits, the only real difference being the nature of the rock which hosts the mineralization. The chemistry and mineralogy of these two deposits are also similar to nearby volcanic peridotite-associated deposits, with the notable exception of the absence of chromite. At Sherlock Bay the mafic to felsic volcanic setting, and the chemistry and mineralogy of the deposit bear little comparison with the other deposits.

The metasedimentary hosts are up to a few tens of metres thick, and are characterized by (i) a bedded appearance despite metamorphic foliation; (ii) an abundance of calcic clinoamphibole (tremolite/actinolite, or hornblende); and (iii) the presence of more quartzose beds, lenses or laminations of recrystallized cherty material. Other non-opaque mineral components are variable but may include calcite or dolomite, plagioclase, biotite or phlogopite, and chlorite. The opaque mineralogy is dominated by nickeliferous pyrrhotite with exsolved pentlandite inclusions, accompanied by variable, lesser amounts of pentlandite, pyrite, chalcopyrite and magnetite. Bulk nickel grades are less than 2 per cent because of the high Fe:Ni ratio and low sulphide volume of the opaque fraction. Sherlock Bay deposit has a subeconomic grade of 0.5 to 0.75 per cent nickel and a much lower bulk Ni:Cu ratio of 5 compared with values of 13 and 17 for Cruickshank and F shoot respectively.

There are gross similarities between the barren sulphidic metasediments common in mafic to ultramafic volcanic sequences (see Chapter 5) and the rare mineralized metasediments being considered here. Available evidence (summarized by Groves and others, 1979) favours a hydrothermal volcanic-exhalative origin for the barren metasediments with sulphur being contributed by magmatic sources. The presence of nickel in the mineralized metasediments suggests that in some circumstances nickel was present in hydrothermal solutions expelled onto the sea floor (cf. Lusk, 1976) and is therefore syngenetic. The lateral persistence of the mineralized metasediments, and the lack of any directly contiguous nickel sulphides in ultramafic rocks, argues, against any known layered sedimentary-associated deposits being a result of nickel introduction either during metamorphism or diagenesis. Further data are required, but in the meantime this apparently rare type of deposit is regarded as volcanic-exhalative in origin.

YILGARN BLOCK

CRUICKSHANK SHOOT (31°27′50″S; 121°52′35″E)

Formerly known as Gigantus prospect, this shoot is situated at the northeastern end of the Tramways group (Fig. 55). A soil geochemical anomaly, which WMC investigated by vacuum and percussion drilling in 1969, resulted in the discovery of Cruickshank shoot. Diamond drilling to evaluate the extent of the shoot was carried out in the period 1972 to 1975. Demonstrated resources rank the shoot as a category 4 deposit.

General geological features of the Tramways area are described in Chapter 5.

The Kambalda ultramafic formation is only 90 m thick. It is largely made up of foliated talc-chlorite-dolomite rocks, with minor amphibole-chlorite units near the top and a few lensoid talc-magnesite rocks up to 5 m thick in the lower part.

The footwall metabasalt is fine grained and weakly to moderately foliated, and it may be siliceous and biotitic at the top. This formation is commonly capped by a laminated sulphidic black slate, or in fewer places by a bedded sulphidic cherty metasediment. In some examples the slate grades upwards into the cherty rock. Overlying the slate or chert is a poorly layered tremolite/actinolite, calcite/dolomite, talc, phlogopite, quartz rock, which generally contains between 5 and 20 per cent fine-grained disseminated nickeliferous sulphides (Fig. 84). This rock also contains disrupted, folded and boudinaged layers of fine-grained quartz (recrystallized chert?) up to 5 mm thick. Cherty or actinolitic metasediments and some biotite-quartz-feldspar metatuffs(?) are also present at higher stratigraphic levels within the ultramafic formation.

Sill-like acid to intermediate porphyry intrusions are common in the sequence.

The shoot is interpreted to be within the upper limb of a recumbent anticline which strikes north-northwest. This fold limb dips at about 35 degrees towards the east-northeast. Diamond drillholes GD 110 and GD 115 intersected the hanging-wall metabasalt below the ultramafic formation in the inverted fold limb, which appears to dip steeply towards the west-southwest (McDonald, 1976).

A north-northwest striking reverse fault which dips steeply westwards divides the shoot into the Western Top subshoot and the Main Contact subshoot. Both areas of mineralization are elongate and plunge at 15 to 25 degrees towards the southeast; the dimensions of the shoot in plan projection are at least 750 m long by up to 180 m wide.

Cruickshank shoot consists entirely of contact ore, although much of this is underlain by carbonaceous or cherty metasediment rather than footwall metabasalt (Fig.

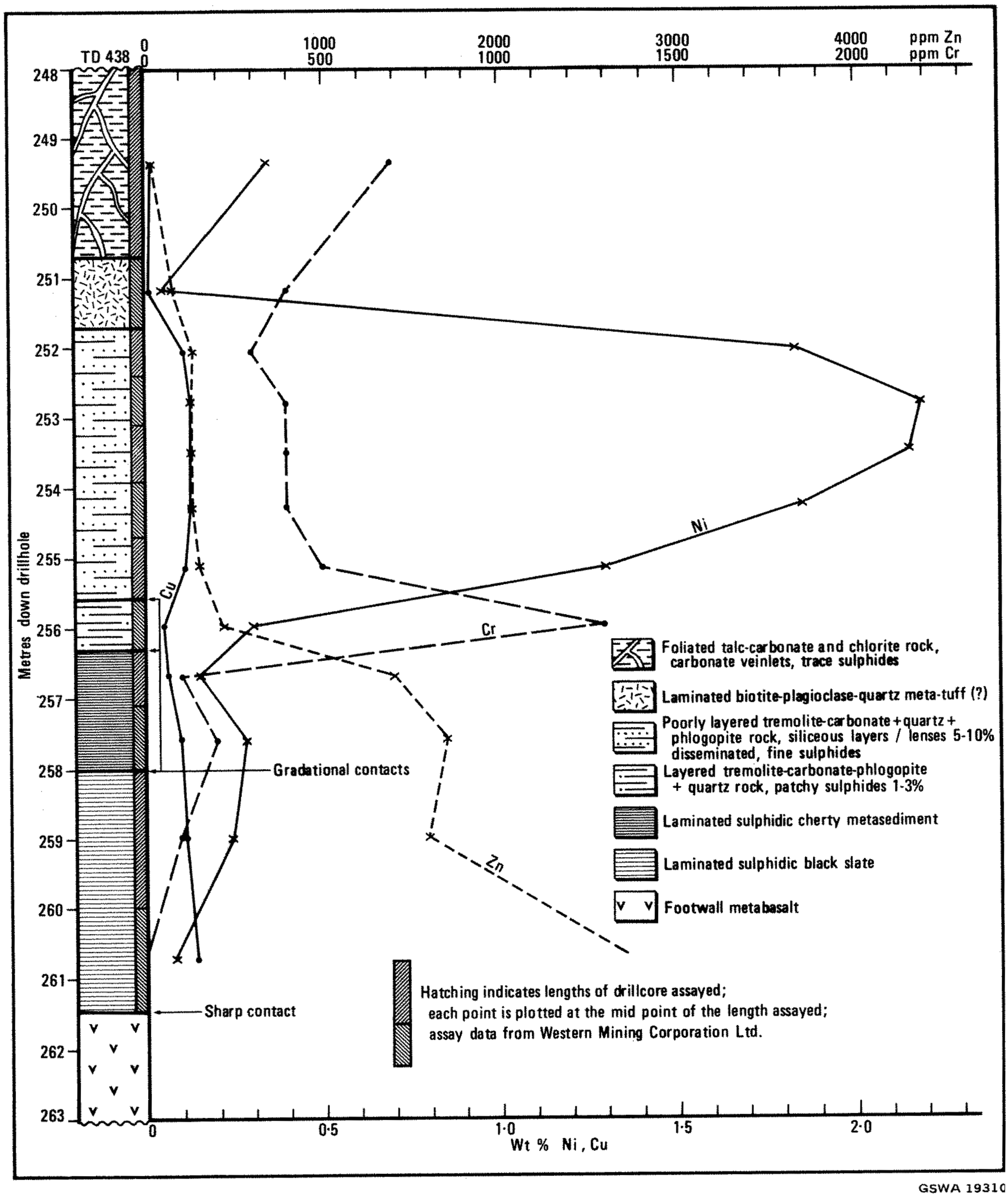


Figure 84. Diagrammatic geological log of part of diamond drillhole TD 438 and geochemical profiles, Cruickshank shoot.

84). Disseminated and rare matrix sulphides occur in the two subshoots previously mentioned, but the ore is present in separate lenses in each subshoot.

The Western Top subshoot includes two small southeast-plunging lenses 150 m apart (north-south), 100 to 200 m long, and up to 50 m wide. Most of the northern lens and the western half of the southern lens are in the oxide zone. The lenses have a gossanous surface expression and extend to depths of 55 m (northern lens) and 90 m (southern lens). The Main Contact subshoot contains two southeast-plunging lenses arranged *en echelon* which have an average thickness of 5 m. The northern lens is terminated by the reverse fault but all other boundaries are defined by nickel assay values. These decline gradually through marginal sub-grade zones in the case of the northern lens; the southern lens has sharper boundaries. The northern lens has a plunge length of 400 m and extends from 55 m to 250 m below the surface, whereas the southern lens has a minimum plunge length of 140 m over a depth interval of 250 m to 380 m.

All mineralization is disseminated throughout the foliated and poorly layered amphibole-carbonate-talc-mica-quartz rock which, from its internal structure and contact relationships, is interpreted to be a metasediment, probably with volcanic affinities.

The mineralization is oxidized to a depth of 40 m, and violarite-pyrite, or assemblages transitional to primary ore, probably occur in the range 40 m to 140 m depth. The primary assemblage is pyrrhotite with less pentlandite, minor pyrite and chalcopyrite, plus accessory magnetite. Average nickel assays are between 1 and 3 per cent, and the mean Ni:Cu ratio is about 13, which is similar to the other deposits in the region. The chromium content of about 0.05 weight per cent is lower than the average for disseminated sulphides in ultramafic rocks and this is reflected by the absence of chromite in the opaque assemblage. Pyrrhotite (nickeliferous), pyrite, minor pentlandite and sparse sphalerite and chalcopyrite occur in the chert and slate.

F SHOOT MOUNT WINDARRA (28°29′10″S; 122°13′50″E)

The blind deposit was discovered by diamond drilling carried out by Poseidon in late-1970. As yet the shoot remains unmined and its demonstrated reserves are 298 138 t averaging 1.87 per cent nickel (5 575 t contained nickel) and 0.11 per cent copper at a cut-off of 1 per cent nickel, which ranks it as a category 5 deposit. The stratigraphy and structure of the Mount Windarra deposit, of which F shoot is a component, are described in Chapter 5, and particular reference should be made to Figure 74 and Table 43.

F shoot corresponds with a group of narrow diamond drillhole intersections (Fig. 85) in the hangingwall metasediment, which is in turn within the Windarra ultramafic formation. This places F shoot stratigraphically above the other mineralization at Mount Windarra, and to the east of a fault known as Charlie shear. Most of the metasediment has the appearance of a layered and foliated amphibolite (hornblende + quartz + plagioclase) some 20 m thick which includes thin, more siliceous sections of a laminated cherty appearance, and rare, thin, magnetite-rich layers and ultramafic layers (Fig. 85). Disseminated-to-matrix and rare breccia sulphides occur in thin, conformable layers up to 4 m thick which are generally confined to the amphibolitic rocks.

Pyrrhotite, pentlandite and pyrite are the dominant opaque phases, chalcopyrite is erratically distributed, and chromite was not observed. Pentlandite is absent as a separate, granular phase from some layers, but pyrrhotite commonly contains flame-like exsolution lamellae of pentlandite. Nickel tenor is generally in the range 1 to 6 per cent and the bulk Ni:Cu ratio is 17.

PILBARA BLOCK

SHERLOCK BAY DEPOSIT (20°48′50″S; 117°32′30″E)

The Sherlock Bay nickel-copper deposit is 40 km east of Roebourne in a featureless plain. The area of the deposit is marked by two small, low ridges which strike east-northeast and are on the northern rim of an ovoid granitoid-gneiss body adjacent to the Sholl shear zone (Fig. 13). An occurrence of buff-coloured, silicified and ferruginous chert with some chrysocolla and malachite staining is shown on the northern margin of the western ridge on the Roebourne Geological Sheet (Ryan, 1966), about 1 km west-southwest of Symond Well. This cherty ferruginous outcrop is some 550 m long (parallel to the strike) and represents the surface expression of the No. 2 mineralized zone. There is no outcrop of the eastern part of the deposit (No. 1 zone).

Since 1967 the deposit has been investigated by Australian Inland Exploration (Texasgulf) as summarized in Miller and Smith (1975) and subsequent unpublished company reports. Drilling outlined two east-northeast striking zones containing significant nickel mineralization which are called the No. 1 and 2 mineralized zones by Miller and Smith (1975), as shown in Figure 86. These authors estimated identified resources of these zones as 75 Mt averaging 0.5 per cent nickel and 0.1 per cent copper. A more recent estimate based on a minimum width of 1.52 m and a cut-off of 0.6 per cent nickel, gives 18 Mt averaging 0.75 per cent nickel to a depth of 900 m. The mineralized zones were originally interpreted as a fracture-controlled vein filling, but re-interpretation, initially by Hester (1974), and later by others (e.g. Groves and others, 1978), envisaged the zones as an integral part of a sedimentary host rock unit which is conformable with the volcanic sequence. Examination of diamond drillcore confirms this.

The volcanic sequence is vertical or steeply north-dipping and forms a lenticular belt about 12 km long and about 1 km wide (Fig. 13) enclosed by gneissic and deformed granitoid rocks. Cream to pale grey-green, foliated and partly laminated meta-tuffs of acid to intermediate composition form most of the sequence, and resemble elements of the Mons Cupri Volcanics of the Whim Creek Group (Marston, 1979). Crystal and lithic fragments are recognizable in many examples, and some tuffs contain horizons or pods of recrystallized chert a few centimetres thick. Metabasalts, metadolerite, metagabbro, and serpentinized peridotite (probably forming intrusions) are subordinate and generally restricted to the southern margin of the belt. Graindorge (1974) estimated that metamorphism attained the transitional greenschist-amphibolite facies.

TABLE 46. AVERAGE CHEMISTRY (10 ANALYSES) OF THE MINERALIZED METASEDIMENTARY UNIT AT SHERLOCK BAY DEPOSIT

	Weight per cent		ppm
SiO_2	54.10	Ni	1 855
TiO_2	0.06	Co	317
Al_2O_3	1.20	Cu	1 865
Fe_2O_3	3.41	Zn	70
FeO	21.43	Cr	176
MnO	0.24		
MgO	6.11		
CaO	8.29		
Na_2O	0.18		
K_2O	0.07		
P_2O_5	0.48		
H_2O+	1.28		
CO_2	0.53		
S	3.78		

Data are from Groves and others (1978)

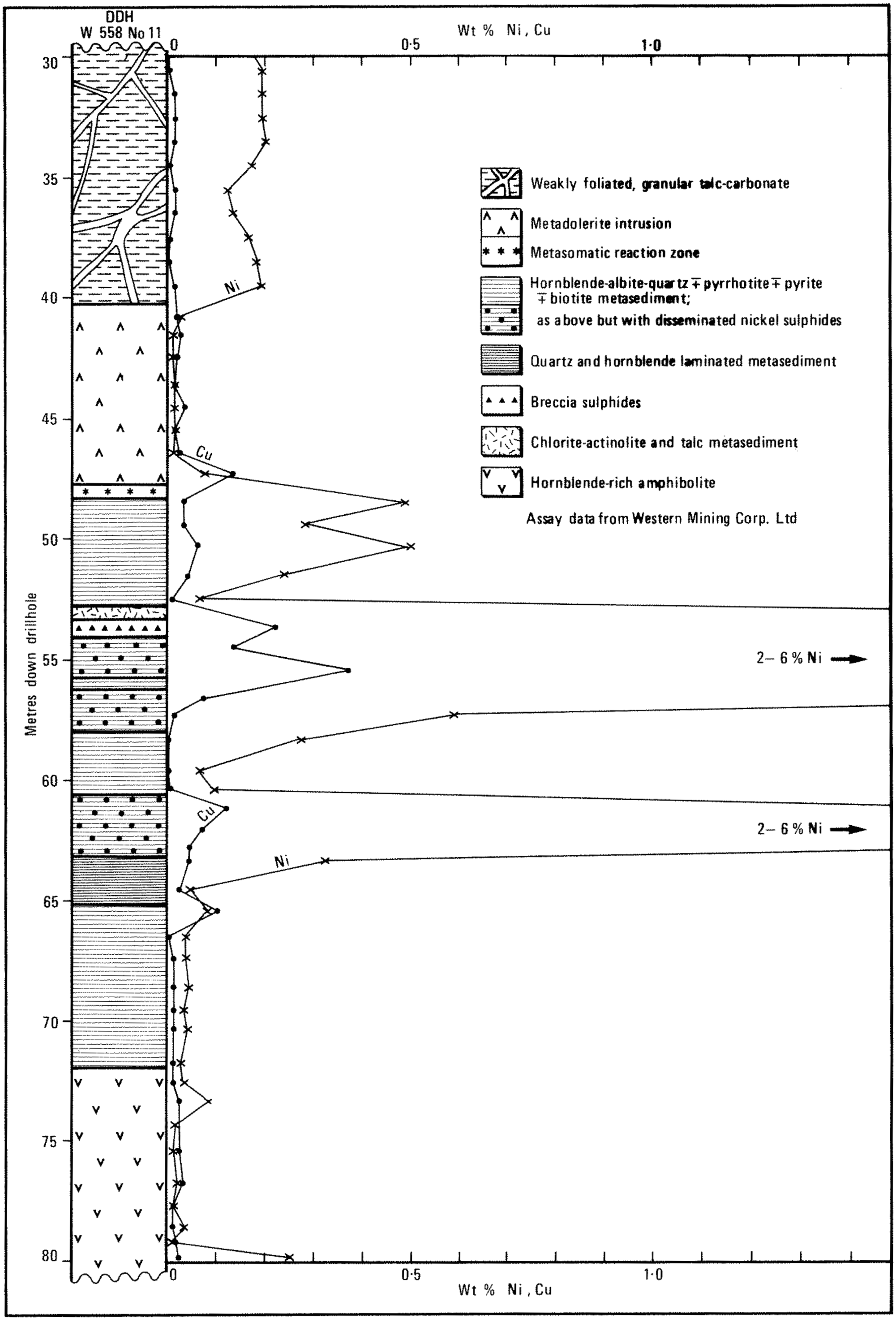


Figure 85. Diagrammatic geological log of part of diamond drillhole W558 No. 11 and geochemical profiles, F shoot, Mount Windarra deposit.

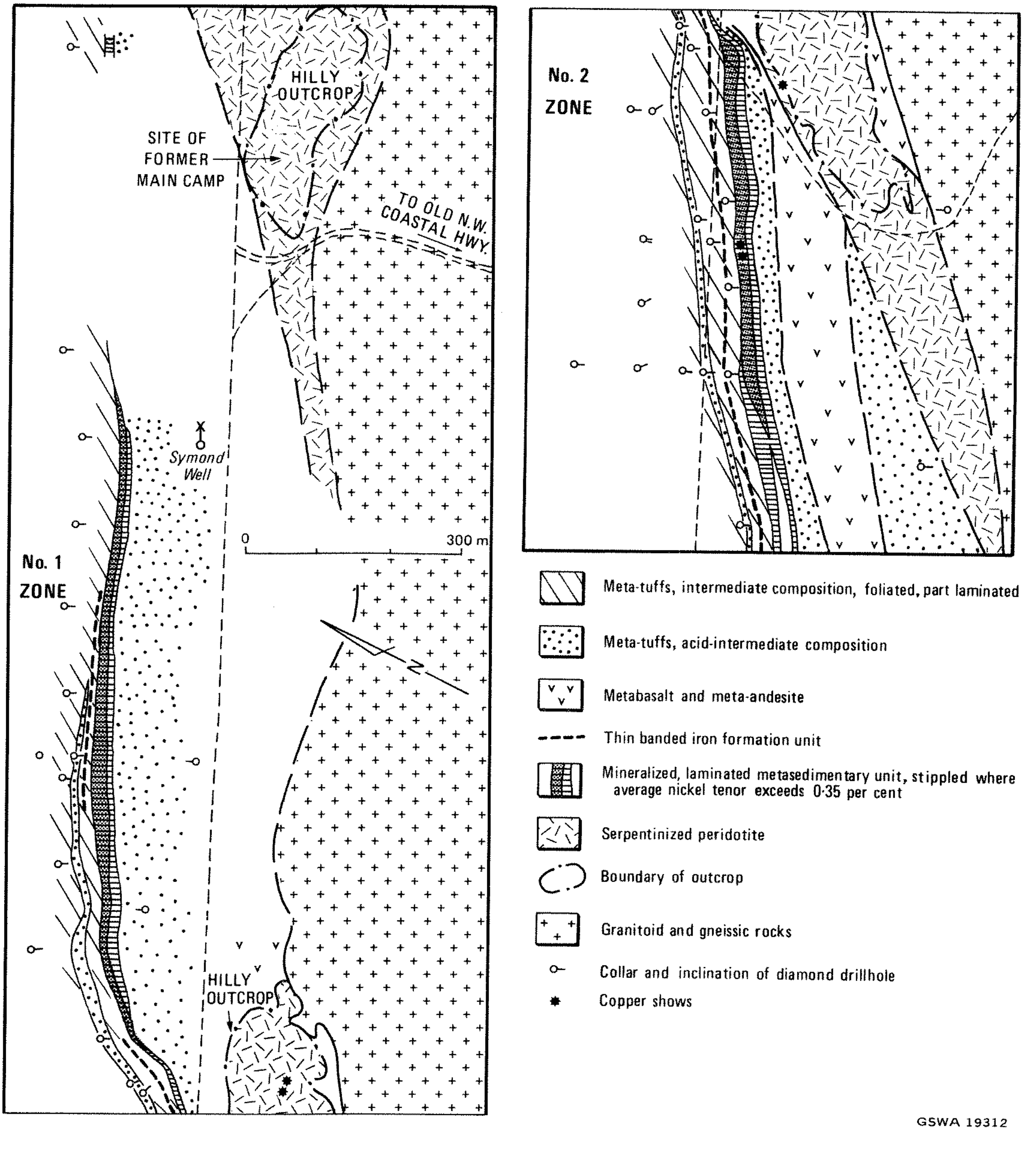


Figure 86. Geological map (interpreted subcrop) of the Sherlock Bay deposit (data from Texasgulf Australia Ltd).

The mineralized unit consists of foliated, fine- to medium-grained, quartz-actinolite + calcite/dolomite + apatite + stilpnomelane + biotite + garnet + chlorite and variable amounts of magnetite and sulphide phases. Actinolite- and quartz-rich layers 2 to 30 mm thick alternate and give the rock a bedded appearance. Groves and others (1978) regarded the mineralogy and chemistry (Table 46) of the unit as being consistent with metamorphic decarbonation of an original iron-, calcium- and magnesium-rich siliceous carbonate rock, possibly a carbonate-facies iron-formation. Compared with most barren sulphidic metasediments associated with volcanic peridotite deposits, that at Sherlock Bay has much lower contents of titania, alumina, soda, potash and zinc and higher iron, lime and phosphorous. The unit has been traced for a distance of some 4 500 m by drilling and magnetic surveys, but is only well mineralized in the east where it attains a true thickness of about 35 m (Fig. 86). To the west the unit becomes more siliceous and is involved in folds; weak copper-dominated sulphide mineralization (bulk Ni:Cu 0.25) occurs here.

Both the Nos. 1 and 2 zones are best mineralized on the northern (hangingwall) side, and appear to plunge downdip or vertically. Thirteen diamond drillholes have penetrated No. 1 zone, but with the exception of one drillhole (SBD 45) which intersected the zone at a vertical depth of about 820 m, all diamond drillhole intersections are above 180 m vertical depth. The No. 2 zone has been intersected by 15 diamond drillholes to a vertical depth of 460 m. Sulphides and magnetite tend to be concentrated in the amphibole-rich beds, with magnetite being more abundant in No. 2 zone. Pyrrhotite is the major phase with lesser pyrite, and minor or accessory pentlandite and chalcopyrite. Pyrrhotite forms aggregates of fine-grained, annealed, polygonal grains and contains exsolved flame-like inclusions of pentlandite; deformation textures are commonly lacking. Pentlandite also occurs in intergranular clusters around pyrrhotite. Pyrite is present as inclusions in pyrrhotite and as larger separate grains. Chalcopyrite is found as separate grains and intergrown with pyrite. Copper or copper-lead-zinc minerals may predominate in some layers (Graindorge, 1974). Textures indicating static metamorphic recrystallization typify sulphide-silicate contacts and some disseminated-matrix sulphides, with amphibole prisms penetrating the sulphides.

CHAPTER 8

Vein-type auriferous-arsenical deposits

SUMMARY AND GENESIS

Deposits of this type are small and few in number, and only one (Mount Martin) has been investigated in any detail. None is commercially important. Most deposits are within ultramafic rocks, and although Mount Martin occurs in metasedimentary rocks, ultramafic rocks are immediately adjacent and possibly subjacent. The ultramafic rocks are commonly strongly altered to carbonate-bearing assemblages and carbonate is an important gangue component of the mineralized veinlets. Gold or auriferous minerals occur with, or near, the nickel arsenide minerals which make up the bulk of the nickel resource. The two largest deposits (Mount Martin, Bamboo) are in faulted or strongly deformed zones.

Existing information suggests that the deposits are of late metamorphic-hydrothermal origin, as carbonate metasomatism appears to follow the peak of regional metamorphism and carbonate alteration is an integral feature of the mineralization.

MINERALIZATION

MOUNT MARTIN DEPOSIT (31°01′00″S; 121°41′05″E)

Mount Martin deposit is 20 km north of Kambalda and 37 km southeast of Kalgoorlie, on the western end of an arcuate tract of mafic to ultramafic rocks which strikes east towards the Carnilya Hill area and north into the Duplex Hill area (Plate 1). The deposit lies within Hampton East Location 45, a freehold property with mineral rights held by Hampton Properties Ltd. In 1967 Great Boulder began exploration for gold in an attempt to find ore to supplement declining production from Fimiston. A considerable effort was expended on the deposit and surrounding area in the period 1967 to 1971, including extensive diamond drilling, shaft sinking and driving at Mount Martin itself. Nickel was discovered associated with the gold mineralization, but the deposit was thought to be of no commercial interest because of low, erratic nickel and gold tenors and a high arsenic content. With the merging of Great Boulder into WMC, subsequent exploration has been carried out by WMC but this has been mainly limited to geological mapping and re-assessment of Great Boulder's data. Higher grade nickel resources have been estimated at 160 000 t averaging 2 per cent nickel and 2.3 per cent arsenic. Gossanous material assays about 1 500 ppm nickel, 95 ppm copper and nearly 1 000 ppm arsenic on average. The gossans occur at the southern end of the deposit.

Outcrop is poor at the deposit itself, but is better to the east where north-northwesterly striking talc-carbonate, talc-chlorite, serpentinite and amphibole-chlorite rocks punctuated by metasedimentary units are found. Deformation was more intense on the western margin of this ultramafic tract, as reflected by dynamic metamorphic fabrics. The deposit occurs in layered and foliated pelitic to siliceous metasediments to the west of the ultramafic rocks, though a narrow lenticular ultramafic unit occurs west of the metasediments which host the deposit. This alternation of ultramafic and sedimentary lithologies may be the result of folding; dips are moderate to steep towards the west. The metamorphic grade attained was locally high; as indicated by the development of kyanite in some pelitic schists.

The deposit consists of a complex system of quartz-carbonate-sulphide-arsenide veins which has a long axis oriented parallel to the strike (north-northwest). Drilling to a vertical depth of 240 m indicates that the deposit plunges gently towards the north-northwest, is about 800 m long (to that depth) and 90 to 240 m wide. On the basis of a minimum drilled width of 1.82 m and a cut-off of 1 per cent nickel, only seventeen intersections contain 'ore-grade' nickel mineralization. Unfortunately only one of these intersections contains more than 5 grammes per tonne of gold; there is no significant detailed correlation between the occurrence of gold and nickel in the veins. Furthermore, intersections rich in nickel (average 2.2 per cent) are also rich in arsenic (2 per cent or more). The distribution of the higher grade intersections appears to be random. The primary opaque mineralogy of the veins is diverse and includes pyrite, pyrrhotite, pentlandite, chalcopyrite, arsenopyrite, gersdorffite, niccolite, ullmanite, safflorite ((Co, Fe) As_2), minor tellurides and rare free gold.

BAMBOO PROSPECT (20°50′20″S; 120°12′40″E)

The Bamboo prospect is located at the old Bamboo Mining Centre, 56 km east-northeast of Marble Bar, between the Mount Prophecy and Prince Charlie gold mines. Diamond drilling by Woodsreef encountered disseminated gersdorffite at vertical depths of 150 to 200 m in silicified and brecciated, carbonated ultramafic rock, in faulted contact with chlorite-carbonate schist. The best intersections averaged 1.69 per cent nickel over a drilled width of 5.09 m. The ultramafic host is mainly talc-carbonate rock, and forms an arcuate zone some 26 km long which is interpreted by Hickman (in press) as being coincident with a steeply inclined strike fault.

OTHER OCCURRENCES

Travis and others (1976, p.1235) reported two occurrences from the Marble Bar area, at Talga Talga (21°00′50″S; 119°49′20″E) and Fieldings Gully (21°18′15″S; 119°45′30″E) respectively 20 km north-northeast and 15 km south of Marble Bar. Gossanous material assayed up to 1 740 ppm nickel. Both are described as narrow sulphide-carbonate veinlets carrying iron-nickel arsenides and chalcopyrite in ultramafic fragmental rocks that are extensively altered to talc-chlorite-carbonate schists. The veinlets are erratically distributed through ultramafics up to 140 m thick. Olivine-rich ultramafics are not present. Gold mineralization occurs nearby.

CHAPTER 9

Other nickel sulphide deposits

INTRODUCTION

Included here are prospects and occurrences which are not readily assigned to the deposit types described above. Two prospects (Abattoirs, Cowarna Rocks) are in Archaean ultramafic rocks adjacent to cross-cutting early Proterozoic mafic dykes, and thermal effects related to the dyke intrusion seem to be partly responsible for the mineralization observed. None of the deposits appears to be of economic importance.

MINERALIZATION

ABATTOIRS PROSPECT (31°01′25″S; 121°31′40″E)

Abattoirs prospect is 32 km south-southeast of Kalgoorlie and 6 km west of the Kalgoorlie-Kambalda road (Plate 1) near the northeastern corner of Location 53 of Hampton Gold Mining Areas Ltd. North-northwest striking metasediments, and mafic to ultramafic rocks are transected by an east-northeast striking gabbroid dyke known locally as the Celebration Dyke, after the old gold mining centre nearby. The prospect is on the eastern side of a narrow zone of mafic to ultramafic metavolcanic rocks and differentiated mafic intrusive rocks, which extends from Yilmia in the south to the vicinity of the Kalgoorlie abattoir in the north. This zone is to the west of and is probably younger than the Kalgoorlie-Kambalda mafic-ultramafic sequence (*cf.* Gemuts and Theron, 1975). The eastern steeply dipping contact of the Abattoirs mafic-ultramafic zone is probably the stratigraphic base.

Exploration was first undertaken by Placer in 1970-1971 whose results were later reassessed by Falconbridge and Shell Minerals in the period 1973-1976. Placer drilled 9 inclined and vertical diamond drillholes (1 110 m total) spaced over a strike length of 180 m into the eastern contact of a serpentinite forming small lateritized outcrops which outline a unit about 150 m in surface width. Very fine-grained iron-nickel-copper sulphides enclosed in granular aggregates of magnetite were found in a dark, flinty, fine-grained serpentinite within 15 m of its east-dipping intrusive contact with largely unaltered microgabbro. The serpentinite has the appearance of a hornfels. This microgabbro is probably part of the Celebration Dyke which (as indicated by magnetic surveys) reappears, slightly offset to the north, on the western side of the serpentinite. Sulphides occur patchily over a strike of 180 m but only two intersections are of interest: 3 m averaging 3.1 per cent nickel plus copper at 85 m vertical depth in DDH 7; and 1 m averaging 2.7 per cent at 128 m depth in DDH 6. The Ni:Cu ratios of the better grade mineralization are typically between 1 and 2. The possible strike extent of the mineralization has not been properly tested. A vertical percussion drillhole (PDH 8) on the western side of the serpentinite returned an assay of 1.65 per cent nickel over a drilled interval of 26 m in weathered serpentinite.

COWARNA ROCKS PROSPECT (30°51′40″S; 122°18′55″E)

This prospect is 83 km east of Kalgoorlie and 10 km north of Avoca Downs homestead, and is adjacent to the easterly continuation of the Celebration Dyke (Plate 1). The Archaean country rocks strike north-northwest and generally dip moderately west, but outcrop is poor except for a series of low hills of variably ferruginized talc-carbonate rocks with lesser serpentinite, a few narrow ridges of chert or banded iron-formation, and some inconspicuous outcrops of semi-pelitic metasedimentary rocks. The dyke may crop out as rounded boulders of medium- to coarse-grained gabbroid with finer grained chilled margins. Great Boulder carried out exploration in the area, mainly in 1969-1971 (Schwabe, 1972).

Geochemical anomalies derived from soil sampling and follow-up auger drilling were delineated near the southern contact of the dyke with a narrow zone of ultramafic rocks. An east-northeasterly oriented line of percussion drillholes inclined to the east was completed across the ultramafic unit about 100 m south of its contact with the dyke. Concentrations of nickel averaging up to 0.35 per cent nickel and 0.09 per cent copper over a drilled interval of 27 m were found in red-brown and green-grey clays after weathered ultramafic rocks. Later percussion and diamond drilling into less weathered rock below 30 m vertical depth encountered thin intervals of nickel sulphide veins, veinlets and disseminations, the best intersection being a drilled width of 3.05 m averaging 1.1 per cent nickel and 0.63 per cent copper (DDH CD3) at a vertical depth of 46 m. The sulphides (transition zone) consist of pyrrhotite, pyrite, marcasite, violarite, chalcopyrite, cubanite, bornite and covellite associated with small dykes of olivine micropyroxenite and basalt which appear to be derived from subjacent and adjacent olivine gabbroid of the Celebration Dyke (Schwabe, 1972). The ultramafic rock which these small dykes penetrated was probably a serpentinite altered to an olivine-orthopyroxene-magnetite hornfels during emplacement of the Celebration Dyke (Schwabe, 1972).

OTWAY PROSPECT (21°44′10″S; 120°04′40″E)

Unusual nickel mineralization occurs in a fault-bounded wedge of weathered Archaean serpentinite about 1 000 m wide, at Otway prospect, 23 km north of Nullagine (Fig. 13) in the Pilbara Block (Nickel and others, 1979). The occurrence was discovered by C. Otway in 1968 and investigated by Conwest in 1969-1970 who completed four diamond drillholes without finding important mineralization. The serpentinized, cumulus-textured or sheared peridotite is silicified or mantled by siliceous duricrust at the surface. Nickel minerals occur as fine- to medium-grained disseminations, blebs and films in lenses up to 20 m long and 1 m wide in shear zones within the serpentinite. The main nickel minerals are millerite, polydymite and pecoraite with subordinate gaspeite, nullaginite ($Ni_2(OH)_2CO_3$), otwayite ($Ni_2(OH)_2CO_3 . H_2O$), reevesite, and rare pentlandite, parkerite, shandite ($Ni_3Pb_2S_2$), breithauptite (NiSb) and nickeloan greenockite ((Cd, Ni) S). Nickel and others (1979) concluded that the mineralization probably results from hydrothermal and/or metasomatic activity along shears in the serpentinite.

CHAPTER 10

Lateritic deposits

SUMMARY AND GENESIS

Ancient lateritic profiles of soil, sediment and weathered rock are commonly developed over ultramafic rocks in the Yilgarn Block. It is not uncommon for thicknesses of 75 to 100 m to be present. Dissection of these profiles by subsequent erosion is advanced in the Norseman-Wiluna belt. Their age is uncertain, and may vary, but a mid-Tertiary age (Oligocene and/or Miocene) seems likely for most of the laterites in southwestern Australia (Johnstone and others, 1973).

Until recently little attention has been directed specifically towards prospecting for lateritic nickel deposits, and their distribution is certainly wider than might be implied by the few investigated deposits that are described below. Much information stems from exploration aimed at testing the underlying ultramafic rocks for nickel sulphides. Nevertheless, it is reasonable to assume that most deposits, known or yet to be discovered, occur in Norseman-Wiluna belt, and the Southern Cross – Forrestania – Lake Johnston – Ravensthorpe area, simply because ultramafic rocks are so abundant there. The only important exception is the Wingelinna deposit in the Musgrave Block, that seems to result from a rather exceptional geological setting. The major deposits in the Yilgarn Block are in the Kalgoorlie, Leonora-Laverton and Ravensthorpe regions.

There is a conspicuous lack of correlation between the distribution of lateritic nickel versus sulphide nickel deposits, even though both are associated with olivine-rich ultramafic rocks. Many nickel sulphide deposits occur where the weathered zone has been partly stripped off. Lateritic profiles over nickel sulphide deposits may resemble those developed over barren ultramafic rocks, but much of the nickel in lateritic nickel profiles is bound up in clay minerals or chlorite. However, over sulphide nickel deposits, iron oxides (as gossan) commonly develop lower in the profile and hence more nickel is found in iron oxides than in clays. This situation is somewhat idealized as it presupposes a simple weathering profile (Table 47), whereas in many cases this is complicated by the development of multiple limonitic zones, and silicification of former saprolite zones ('caprocks') with renewed leaching below the exposed caprock (Smith, 1977).

In the Western Australian deposits nickel is enriched to average bulk grades of 1.2 to 1.4 per cent, with tonnages in the range of 1 to 100 million. Accompanying cobalt contents are generally less than 0.1 per cent, except in small high-grade deposits located near faults and dolerite dykes where bulk grades may be 3 to 4 times that figure. Discontinuities in bedrock structure may also promote deeper weathering and associated richer nickel values in otherwise commercially unimportant laterite.

TABLE 47. IDEALIZED LATERITIC PROFILE DEVELOPED OVER ULTRAMAFIC ROCKS, EAST YILGARN BLOCK

Zone name	Some alternative names	Composition	Nickel enrichment
Surface	Overburden, alluvium, etc.	Various; unrelated to, or formed as a product of, the degradation of underlying profile	None
Limonite	Ferruginous plinthite (massive), ferralite, laterite (s.s.), ironstone, oxide	Hematite, goethite, kaolinite, silica, magnetite/maghemite, carbonates, gypsum, manganese oxides; indurated top may be called ferricrete, iron cap, duricrust, etc.	In absence of clay zone, Ni and Co may concentrate at base of zone
Clay	Intermediate smectite - quartz nontronite, mottled clay (part), soft saprolite (part)	Brown or green montmorillonitic clays silica	May concentrate in nontronite (iron-bearing montmorillonite)
Saprolite	Soft serpentine, soft saprolite	Antigorite, montmorillonite, silica, magnesite, chlorite	May concentrate in antigorite
Oxidized	Hard saprolite, saprolitic peridotite	Bedrock fragments with clayey rims, silica; grades into fresh bedrock	
(Bedrock)			

Data are mainly from Donaldson and Giorgetta (1979)

Golightly (1979) summarized important factors in the genesis of lateritic nickel deposits as follows:

(a) the mineralogy and jointing of the ultramafic rock (influences original nickel content and susceptibility to weathering);
(b) the climate (generally agreed to be equatorial humid or tropical wet-dry to achieve intense leaching);
(c) the topography (influences the depth of the water table and the groundwater flow);
(d) the geomorphic history (controls the extent of erosion, for example).

All these factors are thought to have applied to Western Australian laterites during their formation. Olivine-rich ultramafic rocks have the highest silicate nickel content and should therefore be the preferred starting material, if all other factors are equal. Lateritization involves the dissolution of olivine and serpentine, movement of elements (particularly magnesium, nickel and silicon) in solution, and precipitation of elements in another location (Golightly, 1979). Mineral solubilities and groundwater flows are therefore very important. Solubilities are mainly dependent on hydrogen ion concentration (pH), and most reactions involving nickel replacing magnesium require that nickeliferous solutions pass from a low-pH to a high-pH environment. Accordingly, Golightly (1979) concluded that important nickel enrichment is restricted to places where groundwater moves down through saprolite to a low water table. This is unlikely to be the case where topography is flat, except on the margins of plateaux or perhaps where there are particularly permeable zones (e.g. faults, rock contacts) in the bedrock.

MINERALIZATION

BANDALUP CREEK DEPOSITS

The main deposit (33°38′20″S; 120°22′10″E) occurs 1 km north of Bandalup Hill, 30 km east-southeast of Ravensthorpe (Plate 1). The general geology of the area is described in Chapter 4 under the heading 'Ravensthorpe deposits'. Thick, irregular intrusions of serpentinized peridotite to dunite, 500 to 3 000 m wide, occur in an arcuate zone some 21 km long, which lies on the northeastern limb of the major syncline and includes bodies in adjacent granitoid rocks (McConnell and others, 1975; Thom and others, 1977). Lateritic weathering profiles up to 80 m thick cover most of the ultramafic rocks, but the principal deposit is at Bandalup Hill where identified resources are estimated by P.M.I. at 15.4 Mt averaging 1.4 per cent nickel (216 200 t nickel).

Between 1964 and 1974 exploration of the ultramafic zone was carried out by PMI. A stream sediment geochemical anomaly led to the discovery of the Bandalup deposit in late 1964, and the resource estimate quoted was based on rotary airblast drilling and bulk sampling from a winze. The emphasis changed to a nickel sulphide search in the same ultramafic rocks in the 1970s, but with no success. Previous exploration was reassessed by WMC In 1975-1976) (McConnell and others, 1975). These workers described the ultramafic parent as a serpentinized 'dunite' (34 to 48 per cent MgO, anhydrous) containing close-packed pseudomorphs after coarse-grained, anhedral olivine and accessory magnetite, which is variably altered to serpentine-talc-magnesite rocks. Units of fibrous tremolite rock (metapyroxenite) occur within the dunite, and the whole intrusion is interpreted as a sill-like body dipping west-southwest at about 50 degrees (McConnell and others, 1975). Nickel contents of the dunite are 1 000 to 3 000 ppm, and copper does not exceed 25 ppm in amount.

Saprolite, silcrete and finally barren pisolitic ferricrete successively overlie the dunite in the lateritic profile, and the Pallinup Siltstone (Late Tertiary age) probably post-dates the formation of the profile.

Smaller deposits occur (i) 10 km northwest of Bandalup Hill, to the north of the Ravensthorpe-Esperance highway (33°34′20″S; 120°10′30″E); and (ii) on the west bank of the Young River (33°34′30″S; 120°58′40″E), 56 km east of Bandalup Hill (Thom and others, 1977).

BULONG COMPLEX DEPOSITS (30°523′10″S; 121°45′20″E).

The general geology of the Bulong Complex, a layered mafic to ultramafic intrusion 35 km east of Kalgoorlie (Plate 1), is described in Chapter 6 under the heading 'Bulong Complex North'. The southern third of the complex is partly within Location 42 of Hampton Gold Mining Areas Ltd, and is crossed at its midpoint by the transcontinental railway. Lateritic and silicified lateritic profiles are developed over the ultramafic components of the complex, particularly along its eastern margin.

Newmont undertook exploration for nickel sulphides in the area in 1967-1969. The Hampton company then reassessed Newmont's data and drilled about 150 widely spaced rotary percussion drillholes to average depths of 10 to 15 m to test for lateritic nickel concentrations. Most drillholes did not penetrate the complete weathering profile, and nickel enrichment was found at several levels in the profile. The best results were from an area 2 100 to 2 750 m north of the railway where laterites overlie the eastern margin of the complex. Nickel tenors ranged from 0.8 to 2.1 per cent and averaged about 1.2 per cent, and a tonnage of some 10 to 15 Mt was indicated. Cobalt values were generally less than 0.2 per cent.

Recent exploration by WMC in the general area has encountered more extensive and more cobaltiferous lateritic deposits in profiles about 30 m thick. Nickel and cobalt may be concentrated in montmorillonitic clays overlying saprolite, or in the ferrugionous part of the profile.

BYRO EAST PROSPECT (26°02′10″S; 116°22′40″E).

Byro East prospect is 23 km slightly north of east from Byro homestead, and about 6 km northeast of Melun Bore (Fig. 3). A north-northwesterly striking body of serpentinized peridotite and minor metapyroxenite some 8 km long is largely mantled by laterite and forms a series of ridges and low hills. The country rocks are predominantly quartz-feldspar-biotite gneisses of Archaean age (Williams and others, 1980).

In the period 1971-1973 Jododex carried out exploration in the area for sulphide and lateritic nickel mineralization. Following soil sampling and a shallow auger drilling programme, 23 rotary percussion drillholes (1 301 m total) were sunk to test geochemical, geophysical and geological (i.e. ultramafic contact) targets. Some nickel enrichment (0.5 to 0.9 per cent nickel) was found in weathering profiles up to 40 m thick. Nickeliferous chlorite (i.e. nimite, see Table 12) was reported. Further drilling indicated a small tonnage (about 100 000 t) averaging 1.4 per cent nickel.

CENTRAL BORE (MURRIN) DEPOSIT (28°46′55″S; 121°52′00″E).

Southwest of Central Bore, some 54 km west-southwest of Laverton (Plate 1), Uren (1975) has reported the possible presence of a large deposit of nickeliferous clay in lateritic profiles overlying serpentinized olivine-rich ultramafic rocks. The profiles generally consist successively of fresh bedrock at the base, silicified serpentinite, nickeliferous clay (about 15 m thick), pallid-zone clays and a ferricrete cap at the top. The nickel content of the clays averages between 0.8 and 1.5 per cent, and a tonnage approaching 100 Mt could be present.

Similar nickeliferous lateritic profiles occur over a north-striking ultramafic body 20 km west-northwest of Central Bore in the area north of Waite Kauri Well.

EUCALYPTUS - PYKE HILL AREA DEPOSITS

These deposits occur on the western side of Lake Carey in a north-striking zone some 35 km long which extends from the Eucalyptus area in the south to Pyke Hill in the north (Plate 1). The best known deposit is 5 km southwest of Pyke Hill and is called Pyke Hill deposit (29°02′55″S; 122°08′55″E). This deposit was explored by a joint venture between Mid-East Minerals N.L. and Westralian Sands Ltd in the period 1968-1973, and identified resources of about 12.82 Mt averaging 1.17 per cent nickel (150 000 t nickel) were estimated. Other deposits are probably scattered throughout the extensive lateritic mantle developed over the north-striking mafic to ultramafic sequence in the area, but little exploration specifically directed towards lateritic deposits has taken place. The presence of possibly commercially significant lateritic nickel mineralization is indicated (i) north of Pyke Hollow (6.5 km south-southwest of Pyke Hill); (ii) 1 km west-northwest of Pyke Hill; (iii) 1.5 km east of Eucalyptus Bore where chrysoprase in silicified saprolitic serpentinite has been worked; and (iv) 3 km north of Pyke Hill on the edge of Lake Carey. All the above occurrences are in profiles developed over bodies of serpentinized peridotite to dunite which appear to be intrusive into the country rocks.

The Pyke Hill deposit occurs over the narrow, northwestern arm of a large 'W'-shaped (in plan) ultramafic body, whose eastern arm extends northwards to Pyke Hill and beyond to the shore of Lake Carey at occurrence (iv) listed above. Percussion and diamond drilling along traverses spaced 122 m apart along strike has outlined a narrow zone of lateritic nickel enrichment at least 2 500 m long and a maximum of 370 m wide. The average thickness of the deposit is 15 to 30 m. Most of the southern half of the deposit appears to be only 60 to 120 m in width, although the drillhole spacing along the traverse lines is irregular and incomplete for proper definition of the deposit. There is, however, little scope for enlargement of the known mineralization because metasediment or felsic porphyry outcrops indicate that the ultramafic unit is not much wider than is outlined by the drilling. Silicified saprolitic serpentinite crops out at the northern end of the deposit. Average nickel contents for the deposit in individual percussion or diamond drillholes range from 0.9 to 1.9 per cent, with peak values being between 1.4 and 2.5 per cent. The nickel content of fresh serpentinite is 1 500 to 2 500 ppm. Nickel enrichment occurs in saprolite containing blocks of weathered serpentinite and in overlying clays. Cobalt contents attain peaks of 0.15 to 0.25 per cent (exceptionally 2.5 per cent) and may coincide with or occur just above peaks in nickel enrichment. The nickel appears to be within serpentine-group and montmorillonitic minerals.

The other occurrences mentioned above do not yet merit further description with the exception of occurrence (iv). Here, exploration by Selco (Sands, 1978) encountered a layer of black manganiferous oxides, cropping out at the base of a pisolitic ferricrete, which assayed 2.8 per cent nickel and 3 per cent cobalt.

MERTONDALE PROSPECT
(28°42′00″S; 121°34′20″E).

Mertondale prospect is 32 km northeast of Leonora and 4 km southeast of Mertondale homestead. Exploration by Australasian Mining Corporation and Mount Margaret Nickel Mines N.L. has outlined a north-northwest striking, narrow zone of nickeliferous laterite some 5 km long, 90 m wide and 6 to 8 m thick. Nickel contents of up to 1.36 per cent have been reported.

SIBERIA (ORA BANDA) AREA DEPOSITS

The lateritic nickel deposits of the Siberia area are within a larger region, 50 to 80 km northwest of Kalgoorlie, which has been explored by WMC since 1966 for both lateritic and sulphide nickel deposits. Laterite is best developed and thickest (up to 100 m) over sill-like olivine-rich ultramafic rocks which occur in the lower part of a metavolcanic to metasedimentary sequence folded into a major northwest-striking syncline (Plate 1; Loftus Hills, 1975). Pattern drilling on east-west traverse lines, initially 610 m apart, with later more closely spaced drilling, has indicated the presence of some 30 Mt averaging 1.3 to 1.4 per cent nickel and 0.08 per cent cobalt, plus another 100 Mt at about 1 per cent nickel. The two best known deposits, both of which have been mined, are in the Siberia area and are called the 'SM7' and 'Linger and Die' deposits. Detailed description is restricted to these deposits, which occur 4 to 7 km east-southeast of the abandoned Siberia townsite. The SM7 and Linger and Die deposits have been exploited by WMC for different purposes: the first as a source of siliceous flux for the Kalgoorlie nickel smelter (the contained nickel is thereby recovered); and the second as a high-grade cobalt ore (plus less valuable but extractable nickel) for direct feed in separate batches into the smelter.

The SM7 deposit (30°15′00″S; 120°59′20″E) is 4 km from Siberia, but is also accessible by a graded haul road from Canegrass, 17 km to the east-northeast. When the deposit was inspected in late 1978, a pit measuring 180 m by 125 m in plan and up to 14 m deep had been excavated. The centre and long dimension of the pit coincides with a weathered dolerite dyke, 15 to 25 m wide, which strikes west-northwest. Either side of the dyke, in the base of the pit is a silicified and ferruginized, medium- to coarse-grained, serpentinized dunite containing pseudomorphs after close-packed, polygonal olivine. Limonitic material, locally with nodules of chalcedony or a sandy matrix, is visible elsewhere, except over and adjacent to the dyke where a pale green saprolitic clay with magnesite nodules is developed. A thin zone (1 to 5 m) of ferricrete occurs at the top of the lateritic profile. Drilling has shown that fresh dolerite and serpentinite are present at depths of 50 to 65 m. Demonstrated reserves to a depth of about 30 m(?) are 841 061 t averaging 1.3 per cent nickel (10 934 t nickel) and 67 per cent silica; about one-third of this tonnage had been mined by 1979. This average nickel content is achieved by blending nickeliferous clay (nimite and nontronite) mainly developed over dolerite and containing about 2 per cent nickel, with silicified dunite and its saprolitic weathering products which generally contain less than 1 per cent nickel.

The Linger and Die deposit (30°16′30″S; 121°00′40″E) is 7 km from Siberia, and can be reached by a branch from the main haul road 1.5 km east of the SM7 pit. The deposit was discovered during detailed drilling for nickeliferous clays developed over the same dolerite dyke exposed in the SM7 pit to the west-northwest. The presence of black manganiferous material in laterite adjacent to the dolerite had been noticed in earlier drilling, but the association of cobalt with manganese was not then known. Two pits have been excavated either side of the west-northwest-striking dolerite, the pits being located on a small fault striking north and dipping east (Schwann, 1979). The southern pit is 200 m long, up to 110 m wide and 16 m deep, and was drilled on a 20 by 5 m grid pattern. The northern pit is 50 m by 50 m in plan dimensions and up to 13 m deep, and was drilled on a 12.5 to 15 m by 5 m grid pattern. A total of 62 500 t averaging 0.34 per cent cobalt (212.5 t cobalt), 1.22 per cent nickel, about 3.4 per cent manganese and 45 per cent silica was mined from November 1978 to March 1979. A cut-off figure of 0.10 per cent cobalt was applied. The in-ground value of the cobalt contained in this tonnage was US$11.7 million based on a cobalt price of US$25.00 per pound.

The lateritic profile is complex and probably results from weathering over a long period with varying water table levels, and considerable late silicification. A typical profile as presently preserved consists of 1 to 5 m of massive or pisolitic limonitic material, locally with silica veinlets, magnesite or calcrete nodules. Below this is 3 to 9 m of brown montmorillonitic clay and limonite with developments of veinlets or massive bodies of silica particularly along faults and joints. Below the clayey limonitic material is further limonite-rich material, commonly with veins or nodules of silica. Peak nickel and cobalt values (1.5 to 2.5 per cent and 0.5 to 1.0 per cent respectively) are generally coincident and found at depths of 6 to 9 m (north pit) and 13 to 15 m (south pit) in the lower part of the clay zone (Schwann, 1979). Two types of ore occur: (i) a siliceous variety with cobaltiferous manganese oxides forming some of the matrix around silica pebbles or colloform growths into cavities; and (ii) a clayey variety consisting of friable manganese oxides in patches and layers (Schwann, 1979). Donaldson and Giorgetta (1979) have identified the following manganese oxides:

Co, Ni todorokite: $(Mn^{2+}, Ca, Mg) Mn_3^{4+}O_7.H_2O$
Co, Ni chalcophanite: $(Zn, Fe, Mn^{2+})Mn_3^{4+}O_7.3H_2O$
Co cryptomelane: $K(Mn^{4+}, Mn^{2+})_8O_{16}$

Schwann (1979) concluded that the linear shape of the deposit probably results from enrichment by groundwaters concentrated along faults. The dolerite dyke may also have acted as a local dam to groundwater flow.

A similar deposit, known as 'Gulch', occurs 5.5 km to the northwest, marginal to the same dolerite dyke.

WINGELINNA DEPOSITS (26°03′25″S; 128°57′50″E.

These deposits are 7 to 8 km southwest of the Surveyor General's Corner (where the Western Australian, South Australian, and Northern Territory borders join) within Aboriginal Reserve 17614 (Fig. 3). Exploration was undertaken by the Southwestern Mining Company Limited (subsidiary of INCO) in the period 1955-1970, and by Nickel Mines of Australia NL in 1971-1972. based on 9 600 m of drilling, demonstrated resources have been estimated at 56.2 Mt averaging 1.24 per cent nickel (697 000 t nickel) and 0.09 per cent cobalt at a cut-off grade of 0.90 per cent nickel, with an additional inferred resource of some 41 Mt at similar grades. To date the deposits have been exploited only for chrysoprase, moss agate and nickeloan magnesite, which have been mainly won from the shallow open cut at the eastern side of the eastern of the two main lateritic nickel deposits.

The Wingelinna deposits overlie the Hinckley Range Gabbro, a component of the Giles Complex, which is in turn part of the Musgrave Block (Daniels, 1974). According to Sprigg and Rochow (1975) the deposits are confined to zones of sheared and altered pyroxenite and olivine-rich ultramafic near the northern contact of the Hinckley Range Gabbro. The ultramafic rocks are deeply weathered (up to 150 m vertical depth), but contacts with relatively fresh gabbroid may be sharp. There are two deposits of lateritic nickel which have an aggregate strike length (north-westerly) of 7.5 km and an average width of 1.5 km (Daniels, 1971). An average thickness is about 75 m. yellow-brown, friable goethite (ochre) with minor kaolin and silica veinlets and some manganese oxide are the main components of the deposits. Some parts are more clayey and contain less nickel. The goethitic material appears to overlie oxidized ultramafic rocks, with a saprolitic clay zone evidently being absent.

YORNUP AREA PROSPECTS

The Yornup area is some 50 km southeast of Bunbury in the southwestern corner of the Yilgarn Block (Fig. 3). The bedrock geology is very poorly exposed, being mantled by laterite and early Tertiary alluvium. According to Wilde (1982) the main Archaean rock type is northeasterly striking quartzo-feldspathic paragneiss. Lenticular units of recrystallized banded iron-formation, quartzite, amphibolite and ultramafic rocks occur within the paragneiss and also strike northeast (Wilde, 1982). In the first half of 1970 Planet began exploration in the area, and, following geochemical and geological surveys, detailed efforts were concentrated on two prospects. These are named Yornup prospect, situated 3.2 km south-southeast of Yornup at the intersection of the Southwest Highway and Seaton Ross Road, and the Palgarup prospect, located 10.5 km south-southwest of Yornup and 2.4 km west of the railway.

At Yornup prospect (34°11′50″S; 116°30′40″E) ultramafic rocks form an east-northeast striking zone in gneissic rocks which is at least 1 500 m long and about 600 m wide, as deduced from float, surface and pit geochemical sampling of the laterite, and magnetic surveys. Twenty diamond drillholes were completed (1 569 m total), of which 13 were inclined and designed to test for sulphide mineralization, and the remainder were vertical and tested for lateritic nickel enrichment. Serpentinized peridotite and pyroxenite (and schistose derivations with anthophyllite, talc and chlorite) and metagabbronorite were encountered in the drillholes. Disseminations and veinlets of sulphides are mainly restricted to metapyroxenite. Pyrite is the main sulphide phase, accompanied by pyrrhotite, pentlandite, chalcopyrite, cubanite, bravoite and rare millerite. However, the amount of sulphide present is very low and nickel assays rarely exceed 0.3 per cent. In the lateritic profile nickeliferous nontronite/montmorillonite and chlorite occur; diamond drillhole DDHY 12A intersected 6.7 m at 16 to 22 m depth averaging 2 per cent nickel and 0.06 per cent cobalt. In other drillholes values of 0.5 to 0.8 per cent nickel were encountered over 3 to 9 m intervals.

At the Palgarup prospect (34°13′20″S; 116°08′15″E) an ultramafic zone is at least 1 000 m long (east-northeast orientation) and about 1 000 m wide. Thirteen vertical diamond drillholes (405 m) were completed to test for lateritic nickel enrichments; core recovery was poor. The best intersection averaged 0.83 per cent nickel and 0.06 per cent cobalt over 8.8 m from a depth of 7 to 15 m.

CHAPTER 11

Resource potential

AMOUNT AND DISTRIBUTION OF MINERALIZATION

An assessment of the State's nickel resources made by the Geological Survey at the end of 1978 is summarized in Table 48. At this time Western Australia's resources represented about 5 per cent of the World's identified total nickel resources and about 14 per cent of the World's identified sulphide nickel resources. Current or foreseeable potential exploitation of these resources on an important scale is likely to be confined to sulphide deposits with a bulk nickel grade of more than 1 per cent, assuming that conventional mining techniques are envisaged. The nickel resources of these deposits are subdivided into seven size categories in Table 50 and Figure 87, and the types of deposits (as defined in Chapter 3) falling into each category are also shown. Mines which have produced or are still producing nickel are restricted to categories 1 to 4, although it can be feasible to exploit smaller individual shoots in a closely spaced group of deposits such as occur at Kambalda and Mount Windarra.

TABLE 48. IDENTIFIED NICKEL RESOURCES OF WESTERN AUSTRALIA, DECEMBER 1978

	Amount of mineralizat'n (Mt)	Bulk Grade (%Ni)	Contained nickel (t)
Sulphide deposits, bulk grade of >1 per cent Ni	123.6	2.10	2 598 000
Sulphide deposits, bulk grade of <1 per cent Ni	801.98	0.56	4 484 000
Lateritic deposits	355.86	1.03	3 679 000
Totals	1 281.44	0.84	10 761 000

It is clear from Figure 87 that volcanic peridotite-associated deposits are the most numerous type found to date, but that many are not of sufficient size to be of commercial importance under present economic conditions. Intrusive dunite-associated deposits are less abundant but do not appear to occur in any particular size category, though the largest deposit in the State (Agnew) belongs to this type. About 45 per cent of the sulphide nickel resource at a 1 per cent nickel cut-off is accounted for by intrusive dunite-associated deposits, and 95 per cent of the resource figure for deposits with a bulk grade below 1 per cent nickel is also contained by this deposit type. The few gabbroid-associated deposits that have been found span a wide range in size, but it is worth remembering that the largest sulphide nickel deposits in the World, at Noril'sk (USSR) and Sudbury (Canada), are of this type. Although the gabbroid-associated deposits typically have a low nickel tenor in 100 per cent sulphides, this is compensanted for by low Ni:Cu and Ni:Co ratios (about 3 and 25 respectively) in times when these by-product metals have a high price.

The spatial distribution of known deposits is clearly dominated by the Archaen ultramafic rocks of the eastern Yilgarn Block (Figure 3, Plate 1). The northern third of the Norseman-Wiluna belt and the southern quarter of the Southern Cross – Forrestania supracrustal belt contain almost all the nickel resources represented by intrusive dunite-associated deposits. The southern third of the Norseman-Wiluna belt contains 87 per cent of the nickel resources represented by volcanic peridotite-associated deposits. In detail, the distribution of these deposits is influenced by petrological, stratigraphic and structural controls as summarized in Chapter 4 and 5. In view of the 15 to 20 areal per cent of outcrop (fresh and weathered bedrock) present in the Norseman-Wiluna belt, there can be little doubt that many more nickel deposits lie beneath the mantle of superficial deposits. The technique for, and cost of, finding these undiscovered resources remain the major exploration problems (see below).

The remaining areas of the Yilgarn Block, and the Pilbara Block must be considered as having a low potential for intrusive dunite- and volcanic peridotite-associated deposits, primarily because olivine-rich ultramafic rocks are so poorly developed, and secondarily because a favourable tectonic setting is largely lacking.

The gabbroid-associated deposits are few in number, and most occur in Archaean intrusions, emplaced penecontemporaneously with volcanic activity or a little afterwards. It may be significant that the only sizable deposit known (Sally Malay) is in a Proterozoic metamorphic belt that has an ensialic, intracratonic setting. Mafic to ultramafic intrusions within the Halls Creek Province may be more prospective than those in Archaean cratons, if analogies are drawn with the Svecokarelian (1 850-1 900 million years old) nickel deposits in Finland (Papunen and others, 1979). The minor gabbroid-associated deposits in the Albany-Fraser province occur in the Fraser Complex, a large block of mafic and minor felsic granulites of possible volcanic origin (Gee, 1979). A similarity of setting with the Lower Proterozoic Thompson (Manitoba) nickel belt in Canada can be suggested (Tyrwhitt and Orridge, 1975) although komatiitic amphibolites are prominent in Manitoba (Peredery, 1979). The Paterson-Musgrave belt (Gee, 1979) can also be included in this comparison although very little sulphide mineralization has yet been found in the Giles Complex (Musgrave Block).

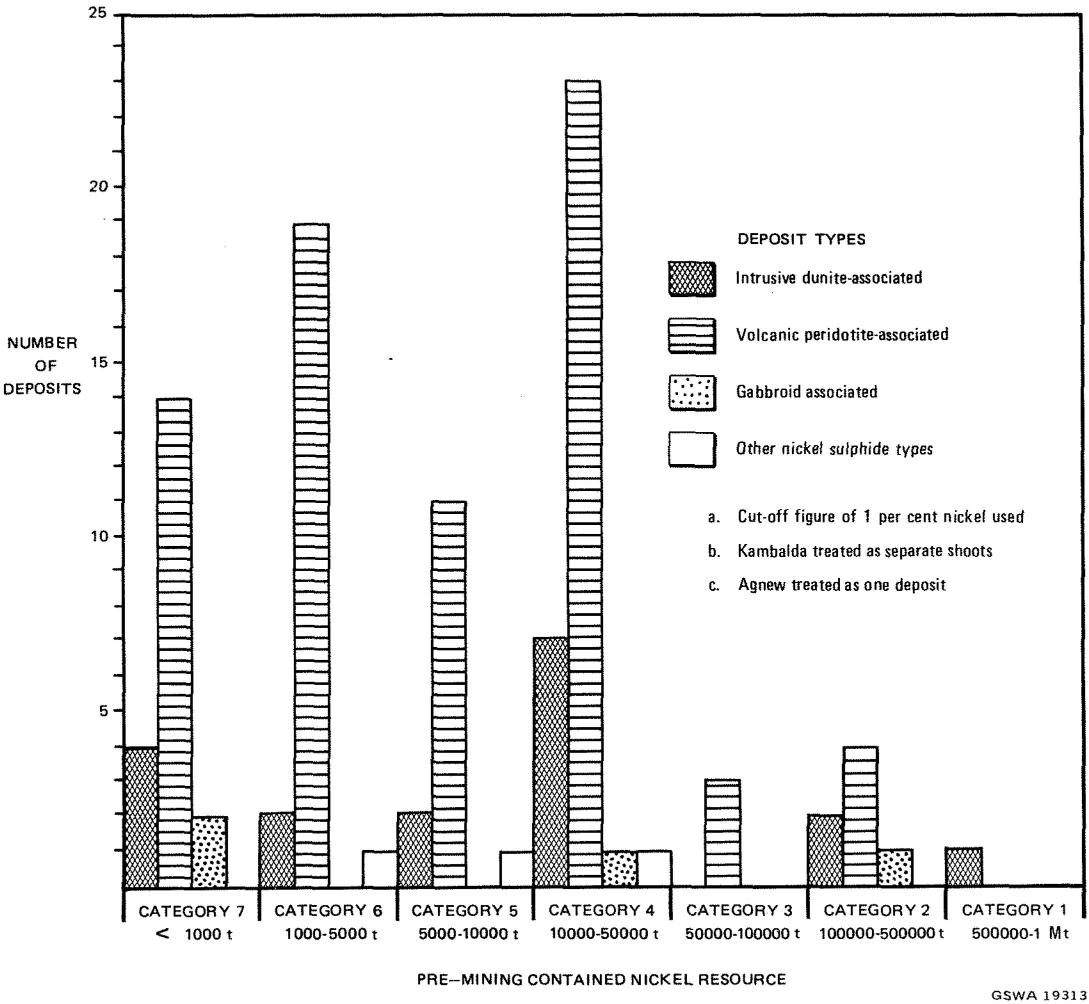


Figure 87. Histogram of numbers of nickel sulphide deposits in defined resource categories for those with stated resources.

The possibility of other types (or geological settings) of nickel mineralization being present should not be overlooked. Before considering exploration targets some of these possible types (partly after Naldrett, 1979) are listed below:

(a) deposits in large sheet-like layered intrusions emplaced (after the Archaean) in cratons or intracratonic basins, but unrelated to flood basalts (e.g. Bushveld, Stillwater, Sudbury);

(b) similar to (a) but in intrusions related to flood basalts (e.g. Insizwa, Duluth, Noril'sk);

(c) deposits in tectonically emplaced ophiolite complexes (e.g. minor deposits in Oregon, Newfoundland, Turkey and Crete);

(d) deposits in Alaskan-type ultramafic complexes emplaced during orogenesis (e.g. minor deposits in Alaska and Czechoslovakia);

(e) polymetallic deposits (e..g U-Ni-Cu-As; Ni-Co-As-Ag-Bi-Cu-Pb) in crystalline basement and clastic sedimentary cover rocks in intracratonic basins (e.g. Key Lake, Saskatchewan; Cobalt, Ontario).

Type (c) and (d) can be fairly safely disregarded, and the large layered intrusions would need to be mainly concealed for their presence to have gone undetected. Weak expressions of type (e) mineralization containing nickel are known from the Ashburton Trough (e.g. Ashburton Downs area; Marston, 1979) but have yet to prove of lasting interest. Indications of uraniferous polymetallic mineralization are found in the eastern arm of the Halls Creek Province, and, of course, major deposits of this type (but apparently lacking nickel) occur to the northeast in the Pine Creek Geosyncline in the Northern Territory.

EXPLORATION TARGETS

Statistically the best chance of finding further mineralization should be within the poorly exposed parts of the Norseman-Wiluna belt and the Southern Cross – Forrestania region.

- For intrusive dunite-associated deposits favourable circumstances include a local pronounced thickening in the ultramafic host, which should stratigraphically underlie a mafic to ultramafic volcanic pile though itself occurring near the top of a sedimentary-felsic volcanic sequence. Proximity to major strike faults is important also. The best target, if these criteria are satisfied, is the stratigraphic base of the olivine-rich ultramafic lens or lenses.

In the case of volcanic peridotite-associated deposits the same criteria apply although the footwall rocks to the olivine-rich ultramafic — an integral part of the mafic-ultramafic volcanic pile — are basaltic. The ultramafic formation and the older and younger basaltic formations should form a thick prism, in which internal stratigraphic disordering may indicate specific targets. In terms of regional stratigraphy a low position for the ultramafic formation is to be favoured. The most important target is the base of the osasal flow of olivine-rich ultramafic rocks, especially where a local thickening in a confining structure is indicated.

With a paucity of deposits there are a few guides for area selection with respect to gabbroid-associated types. Intrusions of tholeiitic affinity in regions with linear tectonic patterns may be relatively more prospective whether in Proterozoic metamorphic belts or Archaean blocks.

Based on these considerations a list of general exploration targets is given in Table 49. Lateritic deposits are not included as they may occur wherever weathering profiles over olivine-rich ultramafics are preserved.

TABLE 49. GENERAL EXPLORATION TARGETS

Deposit type	Region/localities	Remarks
Intrusive dunite	Leonora-Wiluna	Basal contacts of many sills or lenses not adequately tested (e.g. Mount Keith)
	Parker Range -Southern Cross	Small lenses in equivalent stratigraphic position to Forrestania remain incompletely explored
Volcanic peridotite	Kalgoorlie-Norseman	Along strike from known deposits where depths to base of ultramafic piles permit (e.g. Lake Lefroy)
	East and south of Lake Carey	Possible equivalents to Windarra ultramafic formation on east margin of supracrustal belt
	South of Karonie	Possible equivalent of Carnilya ultramafic formation on east margin of belt
Gabbroid	Halls Creek Province	Intrustions with ultramafic components near major faults
	East Pilbara: Soanesville	Encouraging preliminary results, follow-up needed
	West Pilbara: Roebourne and Balla Balla	Little-prospected intrusions in mineralized area adjacent to major tectonic lineament
	Fraser Complex	Possibly a floored intrusive volcanic complex with adjacent major fault
	Musgrave Block	Giles Complex intrusions with ultramafic components

EXPLORATION METHODS

The two main objectives in the exploration for nickel are (i) to define as precisely as possible the extent of olivine-rich ultramafic rocks (less commonly other rock types); and (ii) to locate gossanous material which relates to nickel sulphides at depth. As discussed above the other criteria may influence the priorities given to the exploration of one ultramafic body or sequence versus another.

The two most successful techniques employed in delineating ultramafic rocks have been airborne and ground magnetometry combined with geological mapping, preferably based on large scale (1:25 000 or less) natural colour aerial photography. In areas of little or no outcrop initial exploration relies heavily on ground magnetometry and the proton precession magnetometer is the preferred instrument because of its high sensivity. Anomalies can also be caused by banded iron-formation (few of which are associated with mineralized ultramafic rocks), and it should be remembered that serpentinites are generally more magnetic than talc-carbonate rocks, which in turn are more magnetic than unserpentinized olivine-rich ultramafic rocks. Some of the latter have a very low susceptibility. Well-exposed ultramafic units may exhibit distinctive colour (or tone), vegetal texture and micro-relief on aerial photographs, and in lateritic terrains laterite may be thicker and darker coloured where it overlies olivine-rich ultramafics. On the ground, silicified saprolitic ultramafic rock textures, magnesite nodules and chalcedonic silica fragments may also point to underlying ultramafic rocks.

Unlike many copper-zinc gossans, nickel gossans rarely form conspicuous physical features, and diligent searching is necessary. In initial exploration for nickel gossans it is wise to regard all iron-rich surface material ('ironstone') as being worthy of sampling for chemical analysis, until futher classification is possible. Blain and Andrew (1977), Moeskops (1977a), and Travis and others (1976) have summarized chemical data on Western Australian gossans and the techniques of applying discriminant functions to identify gossans versus ironstones or pseudogossans unrelated to nickel sulphide mineralization. Moeskops (1977a) concluded that most nickel gossans are enriched in nickel (e.g. 3 000 ppm) and copper (e.g. 1 000 ppm), have low Ni:Cu ratios (2 to 6), low zinc (e.g. 140 ppm) and manganese (e.g. 600 ppm) contents, are generally somewhat enriched in bismuth (e.g. 45 ppm), and invariably enriched in platinum, palladium and selenium. High palladium (>15 ppb) and iridium (>5 ppb) are typical (Travis and others, 1976). All the elements mentioned, except for platinum, palladium, iridium and selenium, can be cheaply determined using atomic absorption spectrometry. Mineragraphic study of suspected gossans is important and may confirm their identity without the need for costly analysis of these rare elements. Where some choice is possible careful selection of gossanous material with low contents of exotic (i.e. transported or introduced) iron oxides will often provide diagnositc samples for textural analysis.

Available ultramafic bedrock is also worth sampling, not only to establish the general type of ultramafic rock being dealt with (e.g. volcanic versus intrusive), but to obtain geochemical data which may indicate whether the ultramafic unit is associated with nickel sulphide mineralization. Information is still preliminary but it seems likely that ultramafic rocks have low palladium: iridium ratios — generally less than 10 — (Keays and Davison, 1976; Ross and Keays, 1979), low chromium contents, and that their contained chromites have low zinc contents (Groves and others, 1977). Where disseminated nickel sulphides solely are present, gossan is absent and the host rock then becomes the prime geochemical target.

Where laterite and/or transported overburden is extrensive, it has been found necessary to resort to auger, percussion or even diamond drilling to obtain samples of residual soil or weathered bedrock which have meaningful chemical parameters (e.g. Forrestania region, Mount Keith and Windarra areas). Geochemical anomaly patterns in soil or weathered bedrock generally show that secondary dispersion from the mineralized zone has been limited; movement perpendicular to the strike being typically only a few tens of metres. Biogeochemical prospecting techniques have been little used, but could be employed in reconnaissance surveys delineating ultramafic rocks; *Hybanthus floribunda, Eucalyptus torquata* and *Melaleuca sheathiana* are some of the species so far employed (e.g. Cole, 1973).

Most geophysical methods have been unsuccessful in supplanting geochemical techniques as the basic tool for defining detailed targets for exploratory percussion and diamond drilling. Induced polarization methods have been widely used, but the target most commonly defined has been barren sulphidic, graphitic metasediment which, in a few cases, has led indirectly to the discovery of nickel sulphides because of a close geological association. Electrically conductive overburden and groundwater have restricted the application of electro-magnetic prospecting, but more sophisticated transient and pulse electromagnetic methods offer some promise.

The effectiveness of exploration is also related to the amount of money spent. According to Woodall (1974) some A$170 million in current dollars was spent on nickel exploration in Western Australia in the six years from 1967 to 1972, with the peak occurring in 1970. In the following seven years, from 1973 to 1979, it is estimated that probably no more than A$55 million has been expended. Few new deposits have been discovered in this second period, and with a requisite to concentrate on poorly exposed areas the cost of making a discovery will be much greater than in the first period unless new and improved technology is forthcoming.

TABLE 50. LIST OF NICKEL DEPOSITS WITH IDENTIFIED PRE-MINING RESOURCES

Deposit	Identified resources	Ni%	Contained Ni(t)	Size ctgry	Remarks
INTRUSIVE DUNITE ASSOCIATED					
Agnew	45 000 000	2.05	922 500	1	
Black Swan	4 900 000	0.89	43 610	(4)	0.5% cut-off
Cosmic Boy	5 466 000	2.58	141 154	2	
Digger Rocks	1 232 000	2.21	27 227	4	
Flying Fox	530 000	4.6	24 380	4	
Goliath North	20 450 000	0.62	126 790	(2)	0.5% cut-off
Honeymoon Well	10 000 000	1.10	110 000	2	
Liquid Acrobat	670 000	1.36	9 112	5	
Melon	5 000 000	0.8	40 000	(4)	0.5% cut-off
Mount Keith	263 000 000	0.6	1 578 000	(1)	0.4% cut-off
New Morning	569 500	2.91	16 571	4	
Ratbat	250 000	1.10	2 750	6	
Ravensthorpe 1	473 000	1.49	7 051	5	
Ravensthorpe 4	926 000	0.69	6 389	(5)	0.4% cut-off?
Ravensthorpe 8	250 000	1.95	4 873	6	
Seagull	970 000	1.31	12 707	4	
Sir Samuel	1 500 000	2.0	30 000	4	
Six Mile	60 000 000	0.6	360 000	(2)	0.4% cut-off
South Digger Rocks	3 200 000	1.41	45 120	4	
Weebo Bore	12 600 000	0.67	84 420	(3)	0.4% cut-off
VOLCANIC PERIDOTITE ASSOCIATED					
Alpha Island (East)	—	2.08	—	4	
Alpha Island (West)	—	2.53	—	6	
Beta Island	—	2.92	—	5	
Cameron	—	2.05	—	5	
Carnilya East	500 000	4.2	21 000	4	
Carnilya Hill	42 300	5.6	2 352	6	
Dordie Rocks North	190 500	2.37	4 515	6	
Douglas	—	1.54	—	7	
Duke	—	1.38	—	7	
Durkin	—	3.8	—	2	
East Cooee	—	1.82	—	6	
East Scotia	83 900	2.0	1 678	6	
Edwin	—	3.3	—	4	
Fisher Complex	—	2.31	—	3	
Foster	—	2.7	—	3	
Gellatly-Wroth	—	2.03	—	5	
Gibb	—	2.24	—	4	
Gordon	—	2.49	—	6	
Hunt	—	3.67	—	4	
Jan	—	3.62	—	4	
John	—	1.72	—	6	
Joy	—	1.36	—	7	
Juan complex	—	4.0	—	2	
Ken	—	3.25	—	4	
Loc. 1A Spargoville	365 000	2.53	9 234	5	dilution allowance
Loc. 2 Spargoville	119 250	2.32	2 767	6	dilution allowance
Loc. 3 Spargoville	650 000	2.47	16 055	4	
Loc. 5A Spargoville	250 000	5.0	1 250	6	
Long	—	3.0	—	2	
Loreto	—	2.47	—	6	
Lunnon	—	2.8	—	2	
Marriott	723 780	1.10	7 962	(5)	0.45% cut-off
McMahon	—	3.2	—	4	
Miriam	227 000	1.7	3 856	6	
Munda	245 700	1.65	4 054	6	
Nepean	450 000	4.0	18 000	4	
Pioneer (JH)	32 500	1.1	357	7	
Redross	984 250	3.5	34 449	4	
Republican Hill	—	1.56	—	7	
Ruth Well	70 000	3.0	2 000	7	
Scotia	1 130 000	3.07	34 691	4	
Stockwell	—	1.38	—	7	
Trough Well	20 000	2.5	500	7	
Unimin 1	92 920	1.49	1 384	6	
Victor	—	—	—	5	
Wannaway	1 348 100	2.39	32 219	4	
Wannaway North	392 830	1.09	4 282	6	
Widgiemooltha 3	1 080 000	1.21	13 068	4	
Widgiemooltha Townsite	1 000 000	2.0	20 000	4	
Windarra (Mt) A	1 613 570	2.20	35 499	4	
Windarra (Mt) B	355 130	2.10	7 458	5	
Windarra (Mt) C	88 770	1.60	1 420	6	
Windarra (Mt) D	2 196 750	2.04	44 814	4	
Windarra (Mt) DEO	1 044 930	1.64	17 137	4	
Windarra (Mt) E	314 940	2.47	7 779	5	
Windarra (Mt) G	223 060	1.31	2 922	6	
Windarra (South)	3 200 000	1.94	62 080	3	
14N Mount Edwards	—	1.0	—	6	
26N Mount Edwards	1 700 000	2.5	42 500	4	
132N Mount Edwards	—	1.0	—	5	
166N Mount Edwards	—	2.0	—	5	
332N Mount Edwards	—	1.0	—	5	
360N Mount Edwards	—	1.5	—	4	
384N Mount Edwards	—	2.0	—	5	
47 000S (Republican-Bluebush)	—	1.18	—	7	
50 000S (Republican-Bluebush)	—	2.40	—	7	
83 100W (St Ives)	—	2.59	—	7	
GABBROID ASSOCIATED					
Carr Boyd	1 361 000	1.65	22 456	4	0.57% Cu in resource
Mount Sholl	4 040 000	0.6	24 240	(4)	0.5% cut-off, 0.5% Cu in resource
Sally Malay	3 400 000	2.12	72 080	3	0.79% Cu in resource
LAYERED SEDIMENTARY					
Cruickshank	—	1.74	—	4	
Sherlock Bay	18 000 000	0.75	135 000	(2)	0.6% cut-off
Windarra (Mt) F	298 140	1.87	5 575	5	
VEIN-TYPE					
Mount Martin	160 000	2.00	32 000	4	2.3% As in resource

Deposit	Identified resources	Ni%	Contained Ni(t)	Size ctgry	Remarks
LATERITIC					
Bandalup Hill	15 400 000	1.4	216 200	2	
Bulong	12 500 000	1.2	150 000	2	
Byro West	100 000	1.4	1 000	6	
Central Bore	100 000 000	0.8-1.5	1 200 000	1	
Pyke Hill	12 820 000	1.17	150 000	2	
Siberia region	30 000 000	1.35	405 000	2	0.08% Co in resource
Siberia (Linger & Die)	62 500	1.22	762	7	0.34% Co in resource
Siberia (SM7)	841 000	1.3	10 933	4	
Wingelinna	56 200 000	1.24	697 000	1	0.09% Co in resource
Young River	1 000 000	1.0	10 000	4	

Total contained nickel resources (1% cut-off), including confidential data:

(i) INTRUSIVE DUNITE	1 353 445 t	44.8%
(ii) VOLCANIC PERIDOTITE	1 483 116 t	48.7%
(iii) GABBROID	94 536 t	4.8%
(iv) OTHER SULPHIDE	49 544 t	1.7%
TOTAL SULPHIDE	2 980 641 t	
(v) LATERITIC	2 840 895 t	

Notes:

1. Resource figures are as measured, indicated and inferred from drilling and other geological data. No allowance is made for dilution or loss *during mining, unless stated otherwise.*
2. A cut-off figure of 1 per cent nickel applies unless stated otherwise, (figures in brackets).
3. A dash indicated data unavailable or confidential.

APPENDICES

APPENDIX 1

LIST OF NICKEL DEPOSITS ARRANGED BY 1:250 000 SHEET AREAS

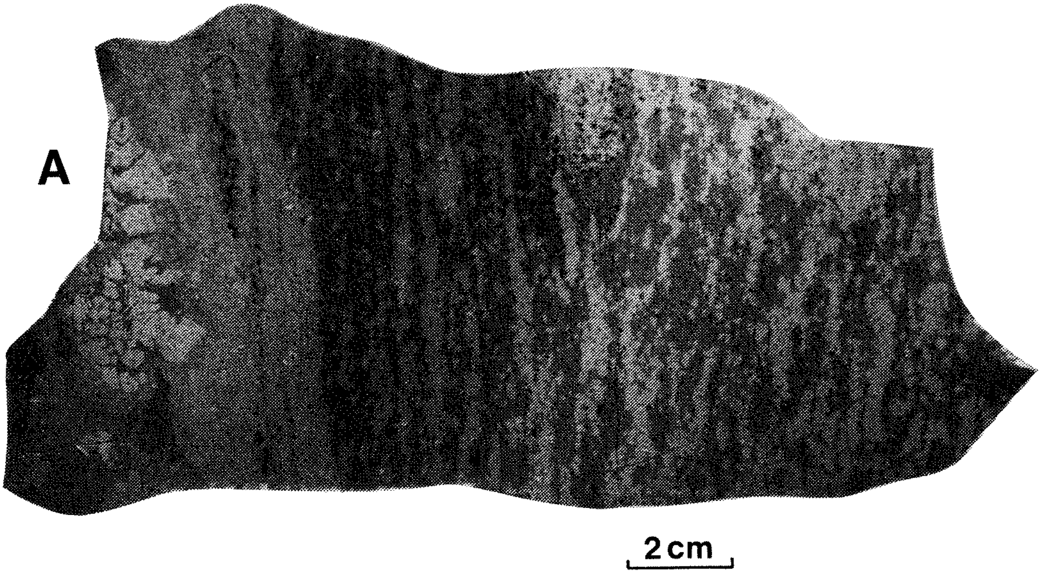
APPENDIX 2

TEXTURAL FEATURES OF SOME NICKEL SULPHIDE ORES IN WESTERN AUSTRALIA

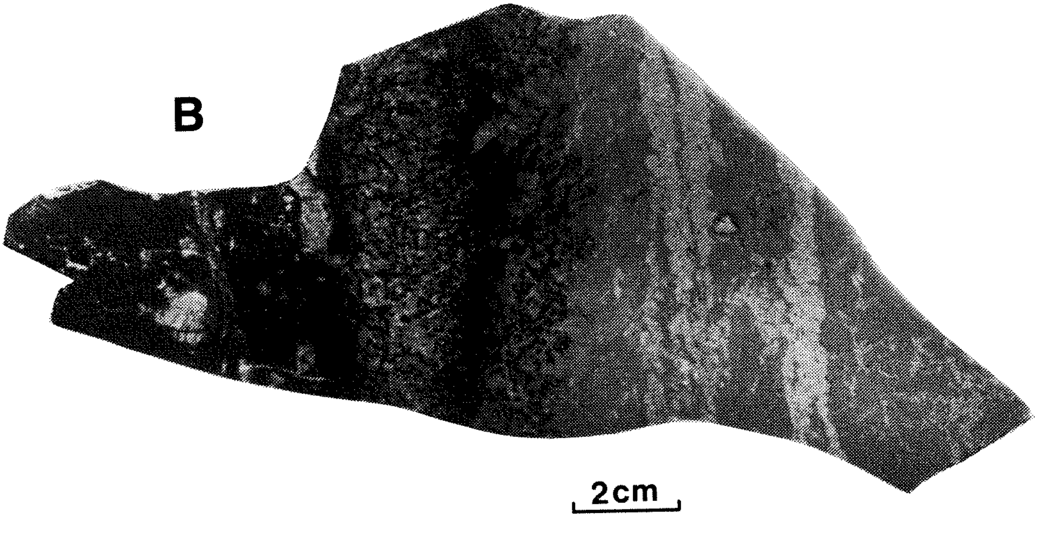
Figure 88 A Layered massive ore, Juan main shoot, Kambalda. Bulk specimen consists of linear pentlandite aggregates (light grey) in a pyrrhotitic matrix (medium grey). Dark grains are mainly spinel. On the left is a lens of fine-grained pyrite (light grey) appearing to cross-cut the pyrrhotite-pentlandite layering. Coarse-grained pyrite cubes with interstitial chalcopyrite occur to the left of the lens of fine-grained pyrite.

B Recrystallized tectonic contact between metabasalt (left) and massive ore (right) consisting of coarse pentlandite layers (light grey) in a matrix dominated by pyrrhotite (medium grey). Metamorphic intergrowth of prismatic hornblende and sulphides occurs in the contact zone. 56517, 650 area, Durkin Deeps 50 subshoot, Kambalda.

A



B



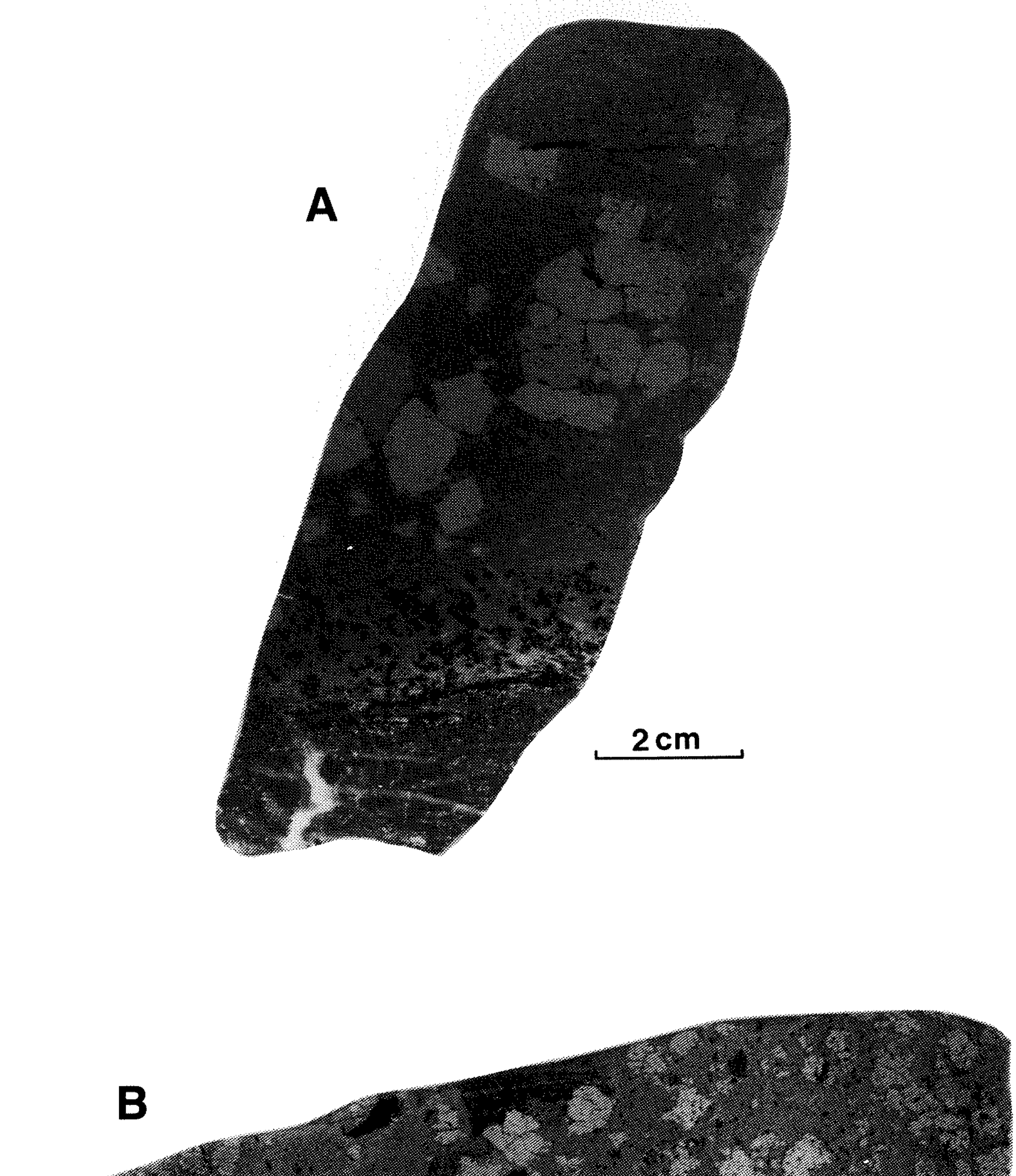

A
2 cm
B
2 cm

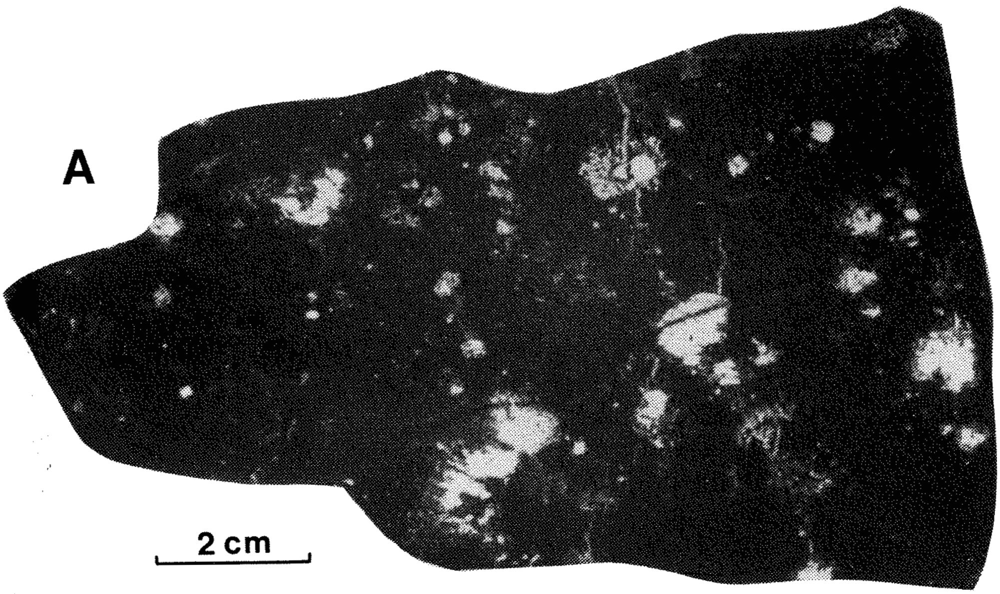
Figure 89 A The basal contact of massive ore with footwall metabasalt (veined by quartz), 1040 stope, Top Surface East subshoot, Lunnon shoot, Kambalda. Large pyrite cubes (pale grey) occur in fine-grained pyrrhotite-pentlandite, with elongate gangue inclusions (black) defining a foliation. Spinel grains (black) are aggregated at the base of the massive ore. 56535.

B Massive pyrrhotite-pentlandite ore with coarse pyrite cubes (pale grey) and wallrock inclusions (dark). 57702, A5 sill drive, A shoot, Mount Windarra

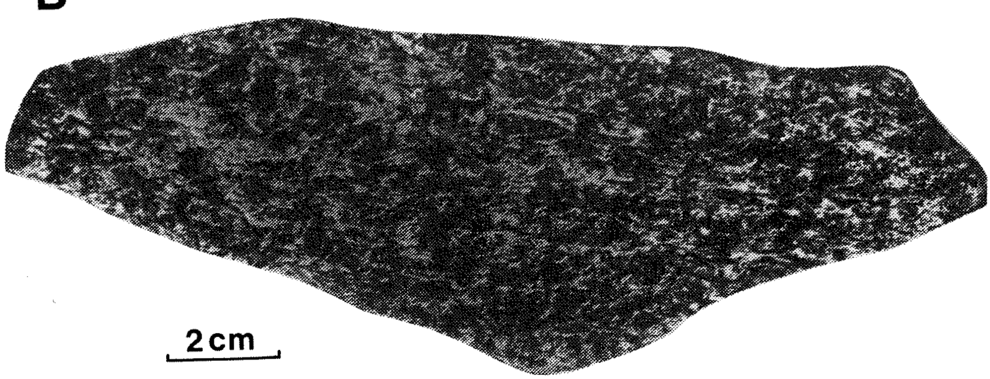
Figure 90 A Blebby disseminated sulphides, consisting of pentlandite, pyrrhotite, pyrite and minor millerite and (chalcopyrite, in massive antigoritic serpentine. 56548, 409 Drive, Durkin shoot, Kambalda.

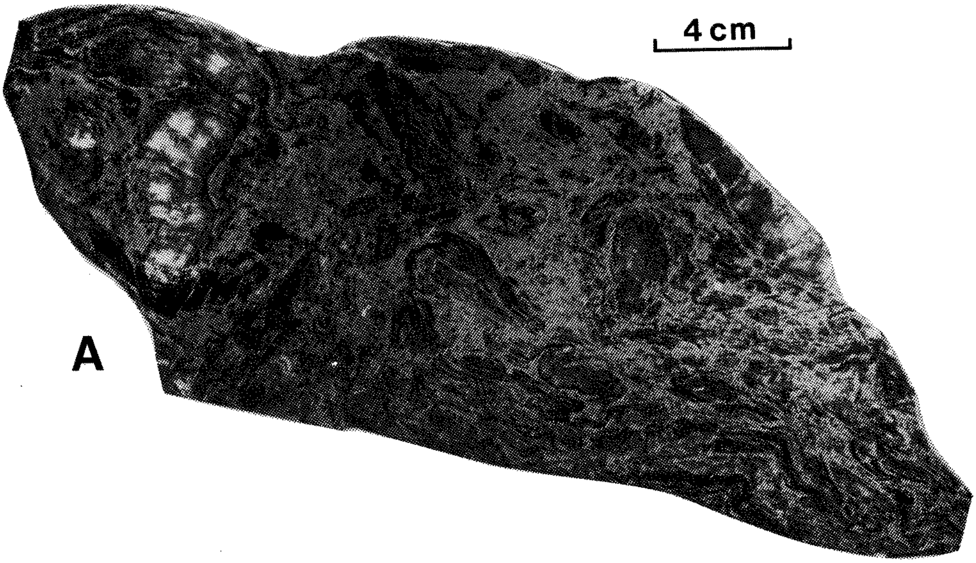
B Foliated, disseminated-to-matrix sulphides (light grey), consisting of pyrrhotite with minor pentlandite and chalcopyrite, in a porphyroblastic talc-carbonate + dolomite rock (medium to dark grey). 56598, B/280 Drive (South end), B shoot, Mount Windarra.

A

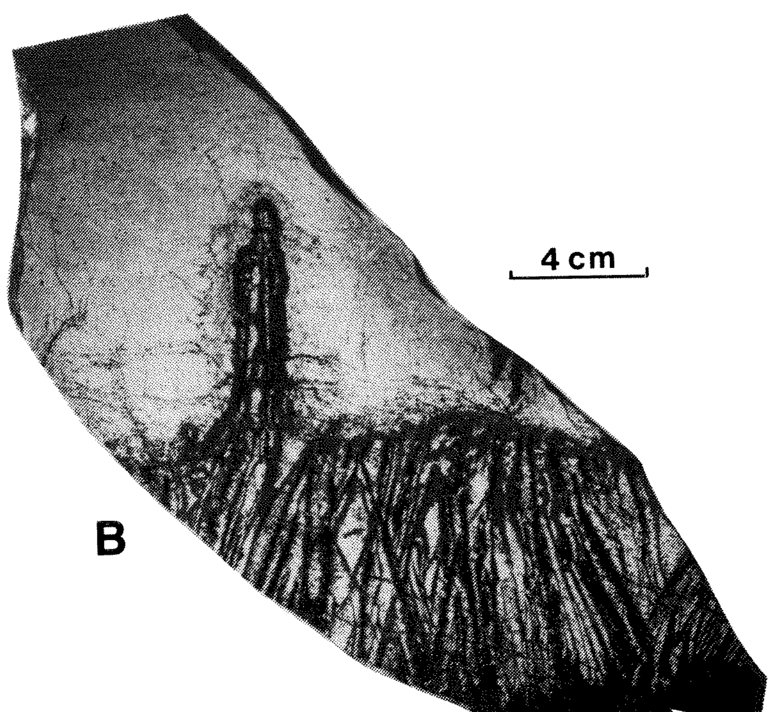


B





A



B

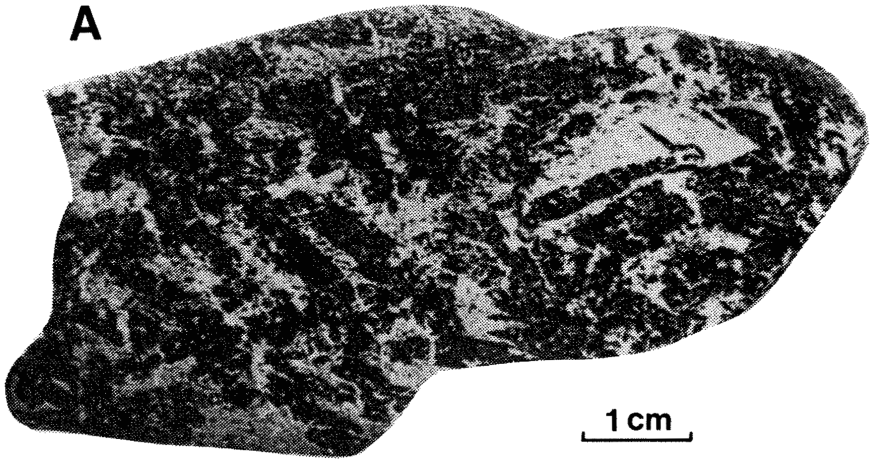
Figure 91 A Breccia ore consisting of folded fragments of laminated pyrrhotitic metasediment in a matrix of pyrrhotite with minor pentlandite, chalcopyrite and pyrite. 57704, A5 sill drive, A shoot, Mount Windarra.

B Coarsely layered pyrrhotite-pentlandite-pyrite massive ore overlying and replacing spinifex-textured talc-chlorite-carbonate ultramafic. Aggregates of zoned spinels (ferrochromite rimmed by magnetite) cluster along contacts between sulphides and silicates. 56523, 628 stope, Hangingwall C subshoot, Lunnon shoot, Kambalda.

Figure 92 A Fractured, serpentinized prismatic olivine (metamorphic) enclosed in a matrix of pyrrhotite and pentlandite with minor chalcopyrite and magnetite. 56164, 6 level crosscut, Mount Edwards 26N.

B Gossan, 1 shoot, Agnew. Granular texture of metadunite is pseudomorphed by pale siliceous material, with goethite (dark grey) occurring interstitially and representing the weathered equivalent of nickel sulphides.

A



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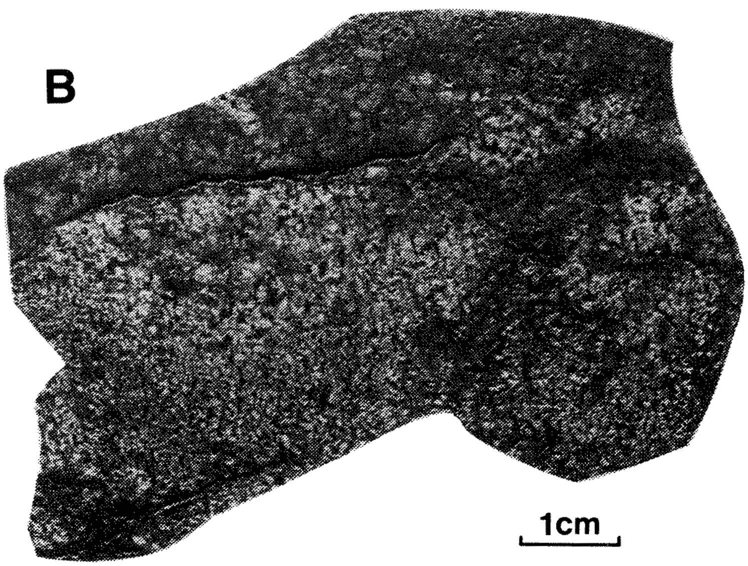

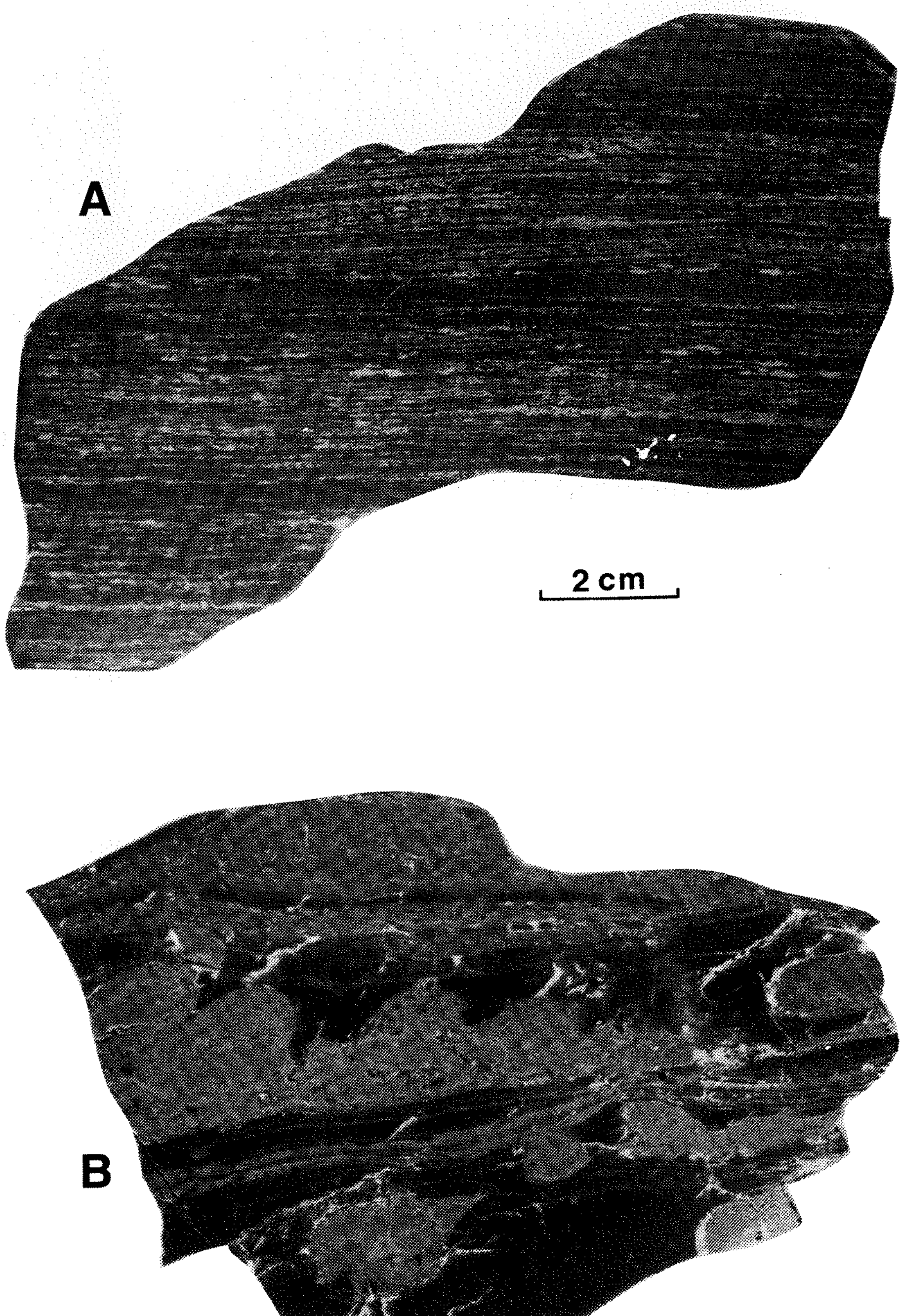
A
2 cm
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Figure 93 A A carbonaceous, pyrrhotitic, cherty metasedimentary rock forming a thin unit in amphibolite. Characteristic laminated texture is well developed. 56105, 4 level drive, Nepean.

B Coarsely laminated cherty metasediment with nodular layers of pyrrhotite with minor pentlandite. 56520, Durkin Deeps subshoot on 6 level at junction with Juan Fault, Kambalda.

Figure 94 Photomicrographs of textures in nickel deposits

A Annealed polycrystalline aggregate of pyrrhotite enclosing larger cracked grains of pentlandite. Gangue inclusions (black) and elongation of pyrrhotite define a foliation. Massive ore, D zone, Hunt shoot, Kambalda. 56527, analyzed light.

B Oriented phyllosilicate inclusions (black) in pentlandite (top) and pyrrhotite. Massive ore, drillhole TD 52, 223.8 m, Edwin shoot, Tramways. 60804, plane polarized light.

C Ferrochromite (grey) rimmed by magnetite (lighter grey) in massive ore. Hangingwall C subshoot, Lunnon shoot, Kambalda. 56523, plane polarized light.

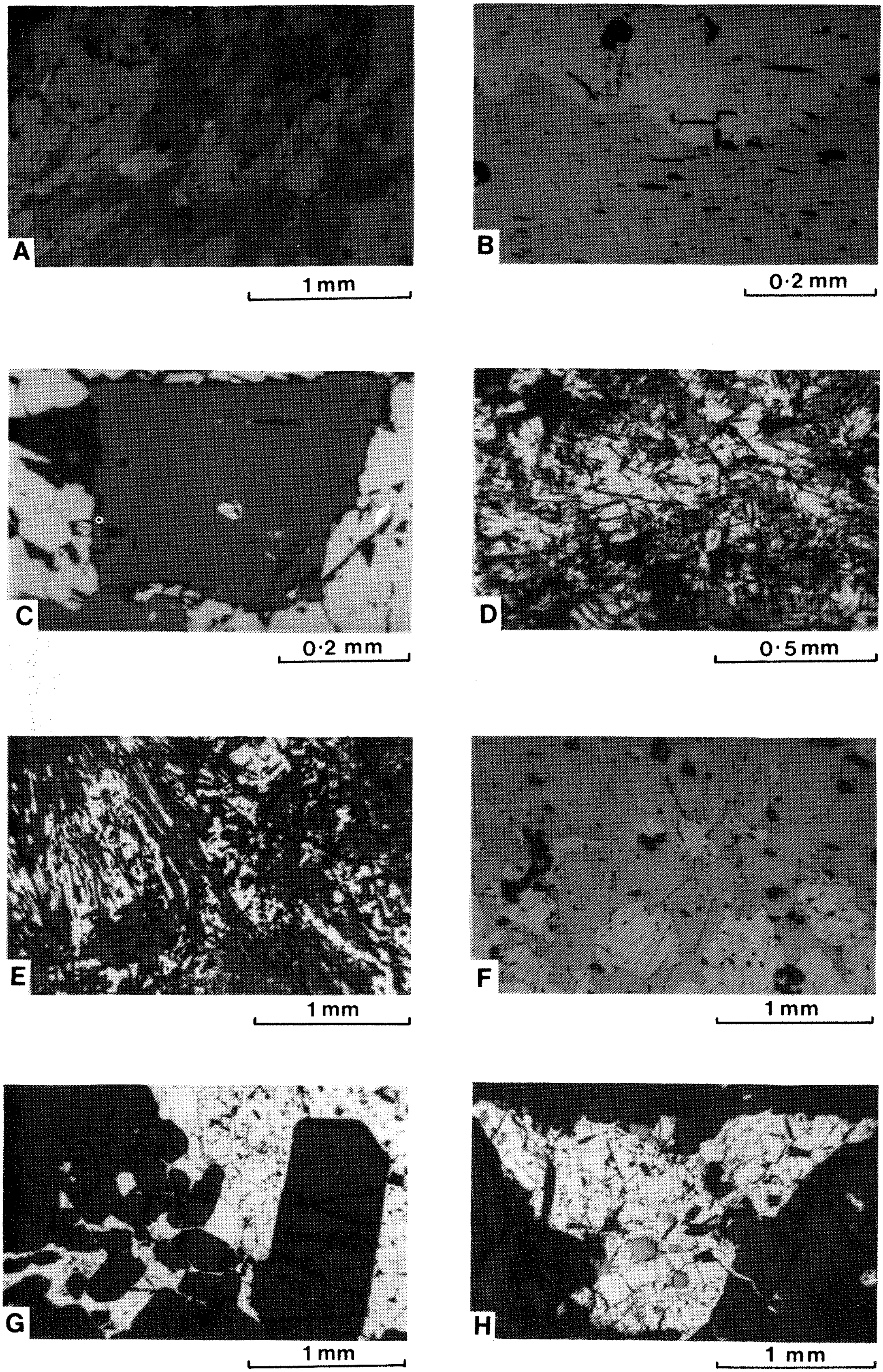
D Static metamorphic recrystallization of pentlandite (white), magnetite (grey) and serpentine (black). Matrix ore, drillhole KD 6041, 502.06 m, Victor shoot, Kambalda. 56509, plane polarized light.

E Static metamorphic recrystallization of amphibole (acicular), olivine (stubby prisms), pyrrhotite and pentlandite (white). Disseminated ore, 2 shoot, Location 3, Spargoville. 56119, plane polarized light.

F Pyrrhotite (pale grey) and lesser pentlandite with abundant gangue inclusions. Massive ore, drillhole WAP 77, 2354.2 ft (717.5 m), 2 shoot, Agnew. 57792, plane polarized light.

G Pentlandite (cracked), pyrite (white) and minor pyrrhotite interstitial to tabular olivine (dark grey) which is altered to serpentine along cracks. Patch of sulphides within granular metadunite, drillhole WAP 114, 1180.95 m, 3 shoot, Agnew. 57816, plane polarized light.

H Pentlandite (cracked), pyrite and chromite (light grey) occupying a triangular space between cracked tabular olivines (dark grey). Talc is present as small flakes (dark grey). Disseminated sulphides in metadunite, drillhole LAD 2, 300.86 m, Liquid Acrobat, Forrestania. 60865, plane polarized light.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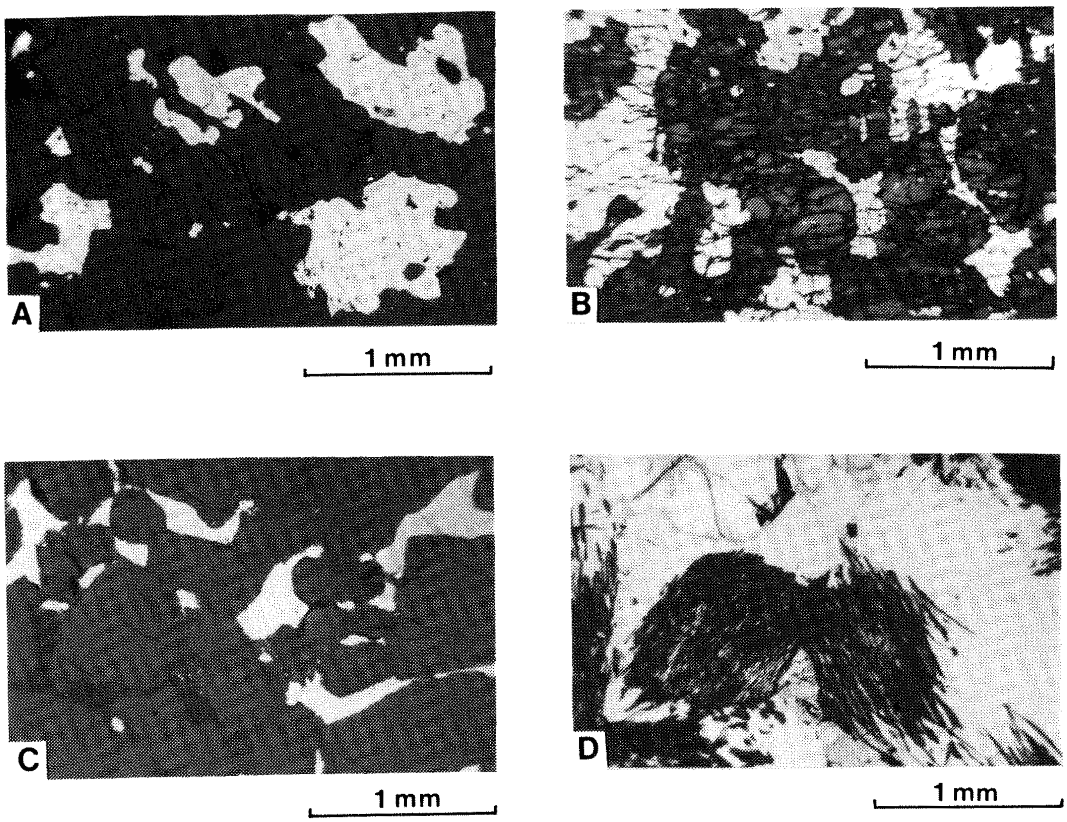
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Figure 95 Photomicrographs of textures in nickel deposits

A Globular aggregates of pentlandite, pyrite and pyrrhotite in olivine aggregate (dark). Disseminated sulphides in granular metadunite, drillhole WAP 77, 2972 ft (905.8 m), 3 shoot, Agnew. 57802, plane polarized light.

B Cracked globular aggregates of pentlandite, pyrite and pyrrhotite in partly serpentinized, granulated olivine aggregate (dark). Disseminated sulphides, drillhole CBD 30, 347.93 m, basal zone, Cosmic Boy. Forrestania. 60871, plane polarized light.

C Pyrrhotite and minor pentlandite (white), and chalcopyrite (pale grey, top right) interstitial to rounded orthopyroxene (marginally altered to anthophyllite). Disseminated sulphides in metapyroxenite, drillhole GD 118, 372 ft (113.4 m), 2 shoot, Carr Boyd Rocks. 57748, plane polarized light.

D Pyrrhotite (right), violaritized pentlandite (top) and chalcopyrite (left) as matrix to tremolite pseudomorphs after orthopyroxene (grey). Drillhole GD 56, 575.5 ft (175.4 m), 3 shoot, Carr Boyd Rocks. 57756, plane polarized light.

REFERENCES

Allchurch, P.D., 1974, Perseverance project, geology and mineral reserves: Australian Selection (Pty) Ltd. (unpublished report) M252.

Anderson, W.B., 1977, North-West Flank orebodies, progress report, November, 1977, Kambalda Nickel Operations: Western Mining Corporation Ltd (unpublished report K2179).

——1978, Kambalda Nickel Operations progress report, June 1978, Juan Shoot: Western Mining Corporation (unpublished report K 2384).

Andrews, P.B., 1975, Spargoville nickel deposits; *in* Knight, C.L. (ed.), Economic Geology of Australia and Papua New Guinea, Metals: Australasian Inst. Mining Metall. Mon. 5, p.89-91.

Archibald, N.J., 1980, Structural and metamorphic evolution of an Archaean greenstone terrain, Norseman-Widgiemooltha area, Western Australia: Univ. West. Australia Ph.D. thesis (unpublished).

Archibald, N.J., Bettenay, L.F. Binns, R.A., Groves, D.I., and Gunthorpe, R.J., 1978, The evolution of Archaean greenstone terrains Eastern Goldfields Province, Western Australia: Precambrian Res. v. 6, p.103-131.

Arden, P.J., 1979, Nickel, gold and molybdenum mineralization in the lake area, progress report, August 1979, Kambalda Nickel Operations: Western Mining Corporation Ltd, (unpublished report K2448).

Arndt, N.T., Naldrett, A.J., and Pyke, D.R., 1977, Komatiitic and iron-rich tholeiitic lavas of Munro Township, northeast Ontario: Jour. Petrology v. 18, p.319-369.

Arndt, N.T., Francis, D., and Hynes, A.J., 1979, The field characteristics and petrology of Archaean and Proterozoic komatiites; Canadian Mineralogist v. 17, p.147-163.

Atkinson, B.K., 1975, A preliminary study of the influence of temperature and strain rate on the rheology of polycrystalline pyrrhotite ores: Neues Jahrb Mineralogie Monatsh. No. 11, p.483-499.

Baragar, W.R.A., and Goodwin, A.M., 1969, Andesites and Archaean volcanism of the Canadian Shield: Proc. Andesite Conf.: Oregon Dep. Geol. Min. Ind. Bull. 65, p.121-142.

Barnes, R.G., Lewis, J.D., and Gee, R.D., 1974, Archaean ultramafic lavas from Mount Clifford: West. Australia Geol. Survey, Ann. Rept 1973, p.59-70.

Barrett, F.M., Groves, D.I., and Binns, R.A., 1976, Importance of metamorphic processes at the Nepean Nickel Deposit, Western Australia: Inst. Mining and Metall. Trans. v. 85, B, p.252-273.

Barrett, F.M., Binns, R.A., Groves, D.I., Marston, R.J., and McQueen, K.G., 1977, Structural history and metamorphic modification of Archaean volcanic-type nickel deposits, Yilgarn Block, Western Australia: Econ. Geol. v.72, p.1195-1223.

Barry, J., 1974 Geochemistry of the Scotia nickel deposit in relation to exploration: Univ. Adelaide Ph. D thesis (unpublished), 99p.

Barton, P.B., Jr., 1973, Solid solutions in system Cu-Fe-S Part 1. The Cu-S and Cu-Fe-S join: Econ. Geol. V. 68, p.455-465.

Bavinton, O.A., 1979, Interflow sedimentary rocks from the Kambalda ultramafic sequence: their geochemistry, metamorphism and genesis: Australian National Univ. Ph.D. thesis (unpublished).

Bavinton, O.A., and Scott, I.R., 1975, An orientation-scale assessment of some ultramafic rocks at Kambalda, for factors reflecting mineralization: Western Mining Corporation Ltd (unpublished report K2120).

Bavinton, O.A., and Keays, R.R., 1978, Precious metal values from interflow sedimentary rocks from the komatiite sequence at Kambalda, Western Australia: Geochim. et Cosmochim. Acta v. 42, p.1151-1163.

Bavinton, O.A., and Taylor, S.R., 1980, Rare earth element geochemistry of Archaean metasedimentary rocks from Kambalda, Western Australia: Geochim. et Cosmochim. Acta v. 44, p.639-648.

Bennett, C.E.G., Graham, J., and Thornber, M.R., 1972, New observations on natural pyrrhotites Part 1. Mineragraphic techniques: American Mineralogist v. 57, p.445-462.

Bennett, C.E.G., Graham, J., Parks, T.C., and Thornber, M.R., 1972a, New observations on natural pyrrhotites Part II. Lamellar magnetite in monoclinic pyrrhotite: American Mineralogist v. 57, p.1876-1880.

Bickle, M.J., Ford, C.E., and Nisbet, E.G., 1977, The petrogenesis of peridotitic komatiites; evidence from high-pressure melting experiments: Earth and Planetary Sci. Letters v. 37, p.97-106.

Binns, R.A. and Groves, D.I., 1976, Iron-nickel partition in metamorphosed olivine-sulphide assemblages from Perseverance, Western Australia: American Mineralogist v.61, p.782-787.

Binns, R.A. Groves, D.I., and Gunthorpe, R.J., 1977, Nickel sulphides in Archaean ultramafic rocks of Western Australia; *in* A.V. Siderenko (ed.), Correlation of the Precambrian: Nauka, Moscow, p.349-380.

Binns, R.A., Gunthorpe, R.J., and Groves, D.I., 1976, Metamorphic patterns and development of greenstone belts in the eastern Yilgarn Block, Western Australia; *in* B.F. Windley (ed.), The Early History of the Earth: Wiley & Sons, London, p.303-313.

Blain, C.F., and Andrew, R.L., 1977, Sulphide weathering and the evaluation of gossans in mineral exploration: Minerals Sci. Engng v. 9, p.119-150.

Blanks, R.F., 1973, The effect of concentrate composition on the smelting and refining of nickel: Australasian Inst. Mining Metall., Papers West Australia Conference 1973, Perth, p.377-390.

Boldt, J.R., Jnr., and Queneau, P., 1967, The winning of nickel: Methuen, London, 487 pp.

Bowes, D.R., 1978, Shield formation in early Precambrian times, the Lewisian complex; *in* D.R. Bowes, and B.E. Leake, (eds.), Crustal Evolution in Northwestern Britain and Adjacent Regions: Seel House, Liverpool, p.39-80.

Brindley, G.W., 1978, The structure and chemistry of hydrous nickel-containing silicate and aluminate minerals: Bull. Bur. Rech. Geol. et Min. (2nd Ser.) Sec. II, No. 3, p.233-245.

Brindley, G.W., and Maksimovic, Z., 1974, The nature and nomenclature of hydrous nickel-containing silicates: Clay Minerals v. 10, p.271-277.

Brooks, C., and Hart, S.R., 1974, On the significance of komatiite: Geology v. 2, p.107-110.

Bunting, J.A., and Williams, S.J., 1979, Sir Samuel, W.A.: West Australia Geol. Survey 1:250 000 Geol. Explan. Notes.

Bunting, J.A., de laeter, J.R., and Libby, W.G. 1976, Tectonic subdivisions and geochronology of the northeastern part of the Albany-Fraser Province, Western Australia: West. Australia Geol. Survey Ann. Rept 1975, p.117-126.

Burt, D.R.L., and Sheppy, N.R., 1975, Mount Keith nickel sulphide deposit; *in* C.L. Knight (ed.), Economic Geology of Australia and Papua New Guinea, Metals: Australasian Inst. Mining Metall. Mon. 5, p.159-168.

Butt, C.R.M., and Sheppy, N.R., 1975, Geochemical exploration problems in Western Australia exemplified by the Mt Keith area; *in* I.L. Elliott, and W.K. Fletcher (eds.) Geochemical Exploration 1974, Developments in Economic Geology 1: Elsevier, Amsterdam, p.391-415.

Campbell, I.H., McCall, G.J.H., and Tyrrwhitt, D.S., 1970, The Jimberlana Norite, Western Australia — a smaller analogue of the Great Dyke of Rhodesia: Geol. Mag. v. 107, p.1-12.

Cawthorn, R.G., and McCarthy, T.S., 1977, Partitioning of nickel between immiscible picritic liquids: Earth and Planetary Sci. Letters v. 37, p.339-346.

Chin, R.J., Hickman, A.H., and Thom, R., in prep., Explanatory notes on the Hyden 1:250 000 geological sheet, Western Australia: West Australia Geol. Survey Rec. 1982/5

Chin, R.J. Williams, I.R., Williams, S.J., and Crowe, R.W.A., 1979, Explanatory notes on the Rudall 1:250 000 geological sheet Western Australia: West. Australia Geol. Survey Rec. 1978/17.

Christie, D., 1975, Scotia nickel sulphide deposit; *in* C.L. Knight (ed.), Economic Geology of Australia and Papua New Guinea, Metals: Australasian Inst. Mining Metall. Mon. 5, p.121-125.

Clarke, D.B., 1970, Tertiary basalts of Baffin Bay: possible primary magma from the mantle: Contributions to Mineralogy and Petrology v. 25, p.203-224.

Cole, M., 1973, Geobotanical and biogeochemical investigations in the sclerophyllous woodland and shrub associations of the Eastern Goldfields area of Western Australia, with particular reference to the role of *Hybanthus floribundus* (Lindl.) F. Muell. as a nickel indicator and accumulator plant: Jour. Applied Ecology v. 10, p.269-320.

Compston, W., and Arriens, P.A., 1968, The Precambrian geochronology of Australia: Canadian Jour. Earth Science v. 5, p.561-583.

Condie, K.C., 1967, Geochemistry of early Precambrian graywackes from Wyoming: Geochim. et Cosmochim. Acta v. 31, p.2135-2149.

Condie, K.C., Macke, J.E., and Reimer, T.O., 1970, Petrology and geochemistry of early Precambrian greywackes from the Fig Tree Group South Africa: Geol. Soc. American Bull. v. 81, p.2759-2776.

Connor, J.J., and Shacklette, H.T., 1975, Background geochemistry of some rocks, soils, plants and vegetables in the conterminous United States: U.S. Geol. Survey Prof. Paper 574-F, 168 pp.

Cooper, J.A., Nesbitt, R.W., Platt, J.P., and Mortimer, G.E., 1978, Crustal development in the Agnew region, Western Australia, as shown by Rb/Sr isotopic and geochemical studies: Precambrian Res. v. 7, p.31-59.

Cox, K.G., and Hornung, G., 1966, The petrology of the Karroo Basalts of Basutoland: American Mineralogist v. 51, p.1414-1432.

Cox, R., 1975. Geochemical soil surveys in exploration for nickel-copper sulphides at Pioneer, near Norseman, Western Australian; *in* I.L. Elliott and W.K. Fletcher (eds.), *Geochemical Exploration 1974, Developments* in Economic Geology 1: Elsevier, Amsterdam.

Cox, R., and Tyrwhitt, D.S., 1975, Pioneer nickel prospects near Norseman; *in* C.L. Knight, (ed.), Economic Geology of Australia and Papua New Guinea, Metals: Australasian Inst. Mining Metall. Mon. 5, p.79-81.

Craig, J.R., and Kullerud, G., 1969, Phase relations in the Cu-Fe-Ni-S system and their application to magmatic ore deposits; *in* H.D.B. Wilson, (ed), Magmatic ore deposits: Econ. Geol. Mon. 4, p.344-358.

Craig, J.R., and Scott, S.D., 1974, Sulfide phase equilibria; *in* P.H. Ribbe, (ed.), Sulphide Mineralogy: Mineralog. Soc. America, 110 pp.

Cronan, D.S., 1972, Regional geochemistry of ferromanganese nodules in the world ocean; *in* D.R. Horn, (ed.), Papers from a conference on ferromanganese deposits on the ocean floor: Office Int. Devade Ocean Exploration, Nat Sci. Fdn. Washington D.C., p.19-29.

——1976, Basal metalliferous sediments from the eastern Pacific: Geol. Soc. America Bull. v. 87, p.928-934.

Dalgarno, C.R., 1975, Nickel deposits of the Widgiemooltha Dome — Redross, Wannaway Widgiemooltha, Dordie *in* C.L. Knight, (ed.), Economic Geology of Australia and Papua New Guinea, Metals: Australasian Inst. Mining Metall. Mon. 5, p.82-86.

Daniels, J.L. 1971, Explanatory Notes Cooper, W.A. 1:250 000 geological sheet: Australia Bur. Mineral Resources.

——1974, The geology of the Blackstone region, Western Australia: West. Australia Geol. Survey Bull. 123.

Davidson, J.E., 1970, A petrological and geochemical study of three diamond-drill holes through the Mt Windarra ultramafics and zone of mineralization: Univ. Adelaide B.Sc Hons. thesis (unpublished).

Davis, G.J., 1972, Geology of the North Range, Koolyanobbing, Western Australia: Univ. West Australia B.Sc. Hons thesis (unpublished).

Davy, R., 1976, Geochemical variations in Archaean granitoids in part of the northeast Yilgarn Block: West. Australia Geol. Survey Ann. Rept 1975, p.137-142.

——1978, A comparative study of the geochemistry of Archaean bedrock in part of the northeast Yilgarn Block: West. Australia Geol. Survey Rept 4.

Day, G.R. Hammond, J.M., and McKay, K.G., 1973, Forrestania Claim Group, Forrestania Western Australia, Progress Report, December 1973: Amax Exploration (Australia) Inc. (unpublished report) M1458.

Docking, K.S., 1977, Flying Fox area, Forrestania, Western Australia, report 1977: Amax Exploration (Australia) Inc. (unpublished report) M1458.

——1978, Manners option area, Forrestania, Western Australia, final report, 1978, Amax Exploration (Australia) Inc. (unpublished report) M1231.

Doepel, J.J.G., 1973, Norseman, W.A.: West. Australia Geol. Survey 1:2500 000 Geol. Series Explan. Notes.

——1975, Albany-Fraser Province; *in* Geology of Western Australia: West. Australia Geol. Survey Mem. 2, p.94-102.

Donaldson, M.J., 1974, Petrology of the Munni Munni complex, Roebourne, Western Australia: Geol. Soc. Australia Jour. v. 21, p.1-16.

——1975, Progress report on the Leinster project 3351 to May 1975: Western Mining Corporation Ltd (unpublished report K2103).

——1980, The behaviour of Ni during metamorphism of some Archaean dunites, Western Australia: Internat. Archaean Symposium, 2nd, Perth 1980, Abstracts, p.62-64.

Donaldson, M.J., and Giorgetta, N., 1979. A mineralogical and chemical study of Ni laterite profiles from the Kalgoorlie region, W.A.: Western Mining Coporation Ltd (unpublished report K2451).

Donelly, T.H., Lambert, I.B., Oehler, D.Z. Hallberg, J.A., Hudson, D.R., Smith, J.W., Bavinton, O.A. and Golding, L., 1978, A reconnaissance study of stable isotope ratios in Archaean rocks from the Yilgarn Block, Western Australia: Geol. Soc. Australia Jour. v. 24(7), p.409-420.

Dow, D.B., and Gemuts, I., 1967, Explanatory Notes Dixon Range, W.A. 1:250 000 Geological Sheet: Australia Bur. Mineral Resources.

Drake, J.R., 1972, The Structure and petrology of banded iron formations at Mount Windarra Western Australia: Univ. West. Australia B.Sc. Hons thesis (unpublished).

Drew, G.J., 1971, A geochemical study of the weathering zone at Mt. Windarra Western Australia: Univ. Adelaide B.Sc. Hons thesis (unpublished).

Duke, J.M., 1976, Distribution of the period four transition elements among olivine, calcic clinopyroxene and mafic silicate liquid; experimental results: Jour. Petrol. v. 17, p. 499-521.

——1979, Computer simulation of the fractionation of olivine and sulfide from mafic and ultramafic magmas: Canadian Mineralogist v. 17, p. 507-514.

Duke, J.M., and Naldrett, A.J., 1978, A numerical model of the fractionation of olivine and molten sulfide from komatiite magma: Earth and Planetary Science Letters v. 39, p. 255-266.

Durney, D.W. 1972, A major unconformity in the Archaean, Jones Creek, Western Australia: Geol. Soc. Australia Jour. v. 19, p.251-259.

Dwyer, J.R., 1977, Mount Windarra stratigraphic project: Western Mining Corporation Ltd (unpublished report).

Eckstrand, O.R., 1975: The Dumont Serpentinite: a model for control of nickeliferous opaque mineral assemblages by alteration reactions in ultramafic rocks: Econ. Geol. v. 70, p.183-201.

Elias, M., and Bunting, J.A., 1978, Explanatory notes on the Wiluna 1:250 000 Geological Sheet, W.A.: West. Australia Geol. Survey Rec. 1978/10.

Elias, M., and Williams, S.J., 1977, Explanatory notes on the Robinson Range 1:250 000 geological sheet: West. Australia Geol. Survey Rec. 1977/6.

Engel, A.E.J., Engel, C.G., and Havens, R.G., 1965, Chemical characteristics of oceanic basalts and the upper mantle: Geol. Soc. America Bull. v. 76, p. 719-734.

Engel, C.G., and Fisher, R.L., 1969, Lherzolite, anorthosite, gabbro and basalt dredged from the Mid-Indian Ocean ridge: Science v. 166, p. 1136-1141.

Eshuys, E. 1975, Unimin-Anaconda joint venture, Widgiemooltha project, final report to 31st December 1974: Union Miniere Development and Mining Corp. Ltd. (unpublished report) M120.

Ewers, W.E., 1972, Nickel-iron exchange in pyrrhotite: Australasian Inst. Mining Metall. Proc. No. 241, p.19-26.

Ewers, W.E., and Hudson, D.R., 1972, An interpretative study of a nickel-iron sulphide ore intersection, Lunnon shoot, Kambalda, Western Australia: Econ. Geol. v.67, p.1075-1092.

Ewers, W.E., Graham, J., Hudson, D.R., and Rolls, J.M., 1976, Crystallization of chromite from nickel-iron sulphide melts: Contributions to Mineralogy and Petrology v. 54, p.61-64.

Ferguson, J., and Currie, K.L., 1972, Silicate immiscibility in the ancient 'basalts' of the Barberton Mountain Land, Transvaal: Nature v. 235, p.86-89.

Gale, G.H., 1973, Palaeozoic basaltic komatiite and ocean-floor type basalts from northeastern Newfoundland: Earth and Planetary Sci. letters v. 18, p.22-28.

Gee, R.D., 1975, Regional geology of the Archaean nucleii of the Western Australian Shield: *in* C.L. Knight, (ed.), Economic Geology of Australia and Papua New Guinea, Metals: Australasian Inst. Mining Metall. Mon. 5, p.43-55.

——1979, Structure and tectonic style of the Western Australian Shield: Tectonophysics v. 58, p.327-369.

——1979a, Explanatory notes on the Southern; Cross 1:250 000 Geological Sheet: West. Australia Geol. Survey Rec. 1979/5.

Gee, R.D., Groves, D.I., and Fletcher, C.I., 1976, Archaean geology and mineral deposits of the Eastern Goldfields: Internat. Geol. Congress XXV, Exc. Guide 42A.

Gelinas, L., and Brooks, C., 1974, Archaean quench-texture tholeiites, Canadian Jour. Earth Sciences v. 11, p.234-340.

Gemuts, I., 1971, Metamorphic and igneous rocks of the Lamboo Complex, East Kimberley Region, Western Australia: Australia Bur. Mineral Resources Bull. 107, 71 pp.

——1975, Miriam nickel prospect, Coolgardie area; *in* C.L. Knight (ed.), Economic Geology of Australia and Papua New Guinea, Metals: Australasian Inst. Mining Metall. Mon. 5, p.98-99.

——1976, Reports on Anaconda's other Ni properties around the Widgiemooltha dome: Widgiemooltha 3, Dordie, Mariners and Munda nickel prospects: Anaconda Australia Inc. (unpublished report) M120.

Gemuts, I., and Theron, A.C., 1975, The Archaean between Coolgardie and Norseman — stratigraphy and mineralization *in* C.L. Knight (ed.), Economic Geology of Australia and Papua New Guinea, Metals: Australasian Inst. Mining Metall. Mon. 5, p.66-74.

Gerasimovsky, V.I., 1974, Trace elements in selected groups of alkaline rocks; *in* H. Sorenson (ed.), The Alkaline Rocks: John Wiley, New York, p.402-412.

Golding, L.Y., and Walter, M.R., 1979, Evidence of evaporite minerals in the Archaean Black Flag Beds, Kalgoorlie, Western Australia: Australia Bur. Mineral Resources Jour. Australian Geol. Geophys. v. 4, p.67-71.

Goldschmidt, V.M., 1958 *in* A. Muir (ed.), Geochemistry: Oxford University Press, London, 730 pp.

Goles, G.G. 1967, Trace elements in ultramafic rocks, *in* P.J. Wyllie (ed.), Ultramafic and Related Rocks: John Wiley, New York, p.353-362.

Golightly, J.P., 1979, Nickeliferous laterites: a general description, *in* International Laterite Symposium: Society of Mining Engineers, New York, p.3-23.

Goss, B.J., 1977, Regional exploration project, Windarra, final report: Western Mining Corporation Ltd (unpublished report K2363).

Gower, C.F., 1976, Laverton, W.A.: West. Australia Geol. Survey 1:250' 000 Geol. Series Explan. Notes.

Gower, C.F., and Boegli, J.C., 1977, Explanatory Notes Rason, W.A. 1:250 000 Geological Sheet: Australia Bur. Mineral Resources.

Gower, C.F., and Bunting, J.A., 1976, Lake Johnston, W.A.: West Australia Geol. Survey 1:250 000 Geol. Series Explan. Notes.

Graindorge, J.M., 1974, Geology and genesis of the Sherlock Bay nickel-copper mineralisation, West Pilbara Region, Western Australia: Univ. West. Australia B.Sc. Hons thesis (unpublished).

Green, A.H., 1978, Evolution of Fe-Ni sulfide ores associated with Archaean ultramafic komatiites, Langmuir Township Ontario: Univ. Toronto Ph.D. thesis (unpublished).

Green, D.M., Nicholls, I.A., Viljoen, M., and Viljoen, R., 1975, Experimental demonstration of the existence of peridotitic liquids in earliest Archaean magmatism: Geology v. 3, p.11-15.

Gresham, J.J., 1978, The Kambalda dome traverse study, final report: Western Mining Corporation Ltd (unpublished report K2389).

Groves, D.I., and Hudson, D.R. 1981, The nature and origin of Archaean stratabound volcanic-associated nickel-iron-copper sulphide deposits, *in* K.H. Wolf (ed.), Handbook of stratabound and stratiform ore deposits, vol 9: Elsevier, Amsterdam, p.305-410.

Groves, D.I., and Keays, R.R., 1979, Mobilization of ore-forming elements during alteration of dunites, Mt Keith-Betheno, Western Australia: Canadian Mineralogist v. 17, p.373-389.

Groves, D.I., Hudson, D.R., and Hack, T.B.C., 1974, Modification of iron-nickel sulfides during serpentinization and talc-carbonate alteration at Black Swan, Western Australia: Econ. Geol. v. 69, p.1265-1281.

Groves, D.I., Barrett, F.M., Binns, R.A., Marston, R.J., and McQueen, K.G., 1976, A possible volcanic-exhalative origin for lenticular nickel sulfide deposits of volcanic association with special reference to those in Western Australia (disc): Canadian Jour. Earth Sciences v. 13, p. 1646-1650.

Groves, D.I., Barrett, F.M., Binns, R.A., and McQueen, K.G., 1977, Spinel phases associated with metamorphosed volcanic-type iron-nickel sulfide ores from Western Australia: Econ. Geol. v. 72, p. 1224-1244.

Groves, D.I., Barrett, F.M., and McQueen, K.G., 1978, Geochemistry and origin of cherty metasediments within ultramafic flow sequences and their relationship to nickel mineralization: Publication Geol. Dept and Extension Service, Univ. West. Australia No. 2, p.57-69.

Groves, D.I., Barrett, F.M., AND McQueen, K.G., 1979, The relative roles of magmatic segregation, volcanic exhalation and regional metamorphism in the generation of volcanic-associated nickel ores of Western Australia: Canadian Mineralogist v. 17, p.319-336.

Gunn, B.M., 1976, A comparison of modern and Archaean oceanic crust and island-arc petrochemistry, *in* B.F., Windley, (ed.), The Early History of the Earth: John Wiley, New York, p.389-403.

Hall, J.S. Both, R.A., and Smith, F.A., 1973, A comparative study of rock, soil and plant chemistry in relation to nickel mineralization in the Pioneer area, Western Australia: Australasian Inst. Mining Metall. Proc. v. 247, p.11-22.

Hallberg, J.A., 1972, Geochemistry of Archaean volcanic belts in the Eastern Goldfields region of Western Australia: Jour. Petrol. v. 13, p.45-56.

—— 1972a, Spilitic pillow lavas at Mount Hunt, Western Australia: Roy. Soc. West. Australia Jour. v. 55, p.1-4.

Hallberg, J.A., and Williams, D.A.C., 1972, Archaean mafic and ultramafic rock associations in the Eastern Goldfields region, Western Australia: Earth and Planetary Science Letters v. 15, p. 191-200.

Hallberg, J.A., Hudson, D.R., and Gemuts, I., 1973, An Archaean nickel sulphide occurrence at Miriam, Western Australia: Australasian Inst. Mining Metall., Papers West. Australia Conference 1973, Perth, p.121-128.

Hallberg, J.A., Johnston, C., Bye, S.M., 1976, The Archaean Marda igneous complex Western Australia: Precambrian Research v. 3(2), p.111-136.

Hancock, S.L., 1978, Fisher shoot, Kambalda Nickel Operations progress report February 1978: Western Mining Ltd. (unpublished report K2380).

Hancock, W., Ramsden, A.R., Taylor, G.F., and Wilmshurst, J.R. 1971, Some ultramafic rocks of the Spargoville area, Western Australia: Geol. Soc. Australia Special Publication 3, p.269-280.

Haughton, D.R., Roeder, P.L. and Skinner, B.J., 1974, Solubility of sulfur in mafic magmas: Econ. Geol. v. 69, p.451-467.

Hayden, P., 1976, Fault and contact movements at Durkin Shoot and their effects on ore: Western Mining Corporation Ltd. (unpublished report K2261).

Head, D.J., 1975, Rock and pebble milling at Kambalda Nickel Operations: Australasian Inst. Mining Metall., Papers South Australia Conference, 1975, Adelaide, p.423-431.

Heath, A.G., and Arndt, C.D., 1976, Nickel exploration of the Carnilya ultramafic belt, Mt Monger, W.A.: Broken Hill Proprietary Co. Ltd. (unpublished report CR 2025).

Hester, B.W., 1974, An interpretation of the geology of the Sherlock Bay nickel prospect: Australian Inland Exploration Co. Inc. (unpublished report) M303.

Hickman, A.H., in press, Geology of the Pilbara Block and its environs: West. Australia Geol. Survey Bull. 127.

Hjarne, U., 1964, Kort anledning till askallige Malm och Bergarters, Mineraliers: Urban Hjarne, Stockholm, p.76.

Hobson, R.A., and Miles, K.R., 1950, Geology of portion of the Mt. Margaret Goldfield: West. Australia Geol. Survey Bull. 103, 136 pp.

Hopwood, T.P., 1976, Conformable elongate orebodies and intrafolial folds parallel to a mineral streaking lineation: *in* W.J. Verwoerd (ed.), Mineralization in metamorphic terrains: Geol. Soc. South Africa Special Publication 4, p.41-51.

Hough, M.J., 1976, Archean ultramafic metavolcanics host to nickel sulphide mineralization, Mt Edwards, Western Australia: Australian National Univ. Ph.D. thesis (unpublished).

Howard-White, F.B., 1963, Nickel, and historical review: Methuen, London, 350 pp.

Hudson, D.R., 1973, Genesis of Archaean ultramafic-associated nickel-iron sulphides at Nepean, Western Australia: Australasian Inst. Mining Metall., Papers West. Australia Conference 1973, Perth, p.99-109.

Hudson, D.R., and Groves, D.I., 1974, The composition of violarite coexisting with vaesite, pyrite, and millerite: Econ. Geol. v. 69, p.1335-1340.

INAL Staff, 1975, BHP/INAL nickel sulphide occurrences of the Widgiemooltha area; *in* C.L. Knight (ed.), Economic Geology of Australia and Papua New Guinea, Metals: Australasian Inst. Mining Metall. Mon. 5, p.86-89.

Jakeš, P., and Gill, J., 1970, Rare earth elements and the island arc tholeiite series: Earth Planetary Sci. Letters v. 9, p.17-28.

Jakeš, P., and White, A.J.R., 1971. Composition of island arcs and continental growth: Earth Planetary Sci. Letters v. 12, p.224-230.

Johnstone, M.H., Lowry, D.C., and Quilty, P.G., 1973, The geology of southwestern Australia — a review: Royal Soc. West Australia Jour. v. 56, p. 5-15.

Joppek, P.E.R., 1975, The geology and geochemistry of rocks associated with nickel sulphide mineralization at Munda, Western Australia: Univ. West. Australia B.Sc. Hons thesis (unpublished).

Kastner, H., Kippenberger, C., Krauss, V., Kruszona, M., Schmidt, H., Kamphausen, D., Leibrucks, M., Rumberger, M., and Wettig, E., 1978, Untersuchungen uber Angebot and Nachfrage mineralischer Rohstoffe X. Nickel: Bundesanstalt fur Geowissenschaften and Rohstoffe, Hanover.

Kavanagh, M.E., 1979, Annual report (1978) on Anaconda's Widgiemooltha dome tenements: Anaconda Australia Inc. (unpublished report) M120.

Kavanagh, M.E., 1979a, Annual report on Anaconda's Sir Samuel area mineral claims: Anaconda Australia Inc. (unpublished report) M159.

Kay, B.D., 1977, Kambalda Nickel Operations progress report, June 1977, Otter/Juan Shoots: Western Mining Corp. Ltd. (unpublished report K2281).

Keays, R.R., and Davison, R.M., 1976, Palladium, iridium, and gold in the ores and host rocks of nickel sulfide deposits in Western Australia: Econ. Geol. v.71, p.1214-1228.

Keays, R.R., Groves, D.I., and Davison, R.M., in prep., Ore element remobilization during progressive alteration of sulfide-bearing ultramafic rocks at the Black Swan nickel deposit, Western Australia: results of a precious metal study.

Keele, R.A., and Nickel, E.H., 1974, The geology of a primary millerite-bearing sulfide assemblage and supergene alteration at the Otter Shoot, Kambalda, Western Australia: Econ. Geol. v. 69, p.1102-1117.

Keeley, G.J., 1974, The geology of the Copper Pit horizon, Ruth Well area, West Pilbara Goldfield, Western Australia: Univ. West. Australia B.Sc. (Hons) thesis (unpublished),

Laurie, J.P., 1977, Fisher Shoot, Kambalda Nickel Operations progress report, May 1977: Western Mining Corporation Ltd (unpublished report K2274).

Lawn, A.M., 1977, Structure and metamorphism at Forrestania, Western Australia: Univ. Melbourne B.Sc., Hons thesis (unpublished).

Leahey, J.E., 1973, The geology and nickel-copper mineralogy of the D Shoot, Mount Windarra, Western Australia: Univ. Tasmania B.Sc. Hons thesis (unpublished).

Leeman, W.P., and Lindstrom, D.J., 1978, Partitioning of Ni^{2+} between basaltic and synthetic melts and olivines — an experimental study: Geochim. et Cosmochim. Acta v. 42, p.801-816.

Legge, P.J., 1975, Weebo Bore nickel prospect; *in* C.L. Knight, (ed.), Economic Geology of Australia and Papua New Guinea, Metals: Australasian Inst. Mining Metall. Mon. 5, p.147-148.

Leggo, M.D., and McKay, K.G., 1980, Forrestania nickel deposits, Western Australia; *in* C.R.M. Butt and R.E. Smith (eds.), Conceptual Models in Exploration Geochemistry — Australia: Jour. Geochem. Exploration v. 12, p.178-183.

Levy, I.W., 1978, A study of the basalts overlying ultramafic formations at Kambalda and Paris — St Ives South: Western Mining Corporation Ltd (unpublished report K2180).

Loftus-Hills, G.D., 1975, Ora Banda lateritic nickel deposits, W.A.; *in* C.L. Knight (ed.), Economic Geology of Australia and Papua New Guinea, Metals: Australasian Inst. Mining Metall. Mon. 5, p. 1010-1011.

Lusk, J., 1976, A possible volcanic-exhalative origin for lenticular nickel sulphide deposits of volcanic association with special reference to those in Western Australia: Canadian Jour. Earth Sci, v. 13, p.451-458.

McCall, G.J.H., 1969, The Archaean succession to the west of Lake Lefroy: Royal Soc. West. Australia Jour. v. 52, p.119-128.

——1971, Some ultrabasic and basic igneous rock occurrences in the Archaean of Western Australia: Geol. Soc. Aust. Special Publication 3, p. 429-442.

——1972, The nickel-sulphide-bearing ultramafic rocks and their environment in the Archaean of Western Australia: Internat. Geol. Congress, XXIV, Proc. Sect. 1, p. 354-362.

——1973, Geochemical characteristics of some Archaean greenstone suites of the Yilgarn structural province Australia: Chemical Geology v. 11, p.243-269.

McCall, G.J.H., and Leishman, J., 1971, Clues to the origin of Archaean eugeosynclinal peridotites and the nature of serpentinisation: Geol. Soc. Australia Special Publication 3, p.281-300.

McConnell, D., Smith, B., Woolrich, P., and Perriam, R., 1975, Annual Report, Ravensthorpe joint venture: Western Mining Corporation Ltd (unpublished report K2159).

McCulloch, M.T., and Wasserburg, G.J., 1978, Sm-Nd and Rb-Sr chronology of continental crust formation: Science v. 200, p.1003-101.

MacDonald, G.A., 1949, Petrography of the island of Hawaii: U.S. Geol. Survey Prof. Paper 214-D, p.51-96.

McDonald, I.R., (ed.), 1976, Terminal report: exploration in the Paris — St. Ives Temporary Reserve — 1965 to September 1975: Western Mining Corporation Ltd (unpublished report) M349.

McKay, K.G., (ed.) 1973, Endeavour option area Forrestania, Western Australia: Amax Exploration (Australia) Inc. (unpublished report) M1523.

——1978, New Morning area, Forrestania, Western Australia, report 1977: Amax Exploration (Australia) Inc. (unpublished report) M1458.

MacPherson, H.G., 1958, A chemical and petrographic study of pre-cambrian sediments: Geochim et Cosmochim. Acta v. 14, p.73-92.

McQueen, K.G., 1979, Experimental heating and diffusion effects in Fe-Ni sulfide ore from Redross, Western Australia: Econ. Geol. v. 74, p.140-148.

——1979a, Metamorphism and deformation of volcanic-associated nickel deposits around the Widgiemooltha Dome, Western Australia: Univ. West Australia Ph.D. thesis (unpublished).

Marjoribanks, R.W., 1978, A review of the geology and mineral potential of the Sir Samuel area; *in* M.E. Kavanagh 1978, Annual report on Anaconda's Sir Samuel Area mineral claims: Anaconda Australia Inc. (unpublished report) M159.

Marston, R.J., 1978, The geochemistry of Archaean clastic metasediments in relation to crustal evolution, northeastern Yilgarn Block, Western Australia: Precambrian Res. v. 6, p.157-175.

——1979, Copper mineralization in Western Australia: West Australia Geol. Survey Mineral Resources Bull. 13.

Marston, R.J., and Kay, B.D., 1980, The distribution, petrology, and genesis of nickel ores at the Juan Complex, Kambalda, Western Australia: Econ. Geol. v. 75, p.546-565.

Marston, R.J., and Travis, G.A., 1976, Stratigraphic implications of heterogeneous deformation in the Jones Creek Conglomerate (Archaean), Kathleen Valley, Western Australia: Geol. Soc. Australia Jour. v. 23, p.141-156.

Martin, J.E., and Allchurch, P.D., 1975, Perseverance nickel deposit, Agnew; *in* C.L. Knight (ed.), Economic Geology of Australia and Papua New Guinea, Metals: Australasian Inst. Mining Metall. Mon. 5, p.149-155.

Mason, B., 1966, Principles of geochemistry: J. Wiley & Sons, New York, third edition.

Mazzucchelli, R.H., 1972, Secondary geochemical dispersion patterns associated with nickel sulphide deposits at Kambalda, Western Australia: Jour. Geochem. Exploration v. 1, p.103-116.

Miller, L.J., and Smith, M.E., 1975, Sherlock Bay nickel-copper; *in* C.L. Knight, (ed.), Economic Geology of Australia and Papua New Guinea, Metals: Australasian Inst. Mining Metall. Mon. 5, p.168-174.

Milne, A., and Mason, M.G., 1975, Kennecott option, Sir Samuel Blocks A & B, Final exploration report: Western Selcast (Pty) Ltd (unpublished report) M1284.

Misra, K.C., and Fleet, M.E., 1973. The chemical compostion of synthetic and natural pentlandite assemblages: Econ. Geol. 68, p.518-539.

Moeskops, P.G., 1973, The Bulong serpentinite and environments of nickel mineralization near Kalgoorlie: Univ. London, Imperial College Ph.D. thesis (unpublished).

——1975, Cupriferous violarities from the Bulong Complex near Kalgoorlie, Western Australia: Australian Mineral Development Laboratories Bull. 20, p.19-31.

——1977, New type of igneous layering due to fractionation of Archaean ultramafic magma: Nature v. 267, p.508-509.

——1977a, Yilgarn nickel gossan geochemistry — a review with new data; Jour. Geochem. Exploration v. 8, p.247-258.

Mookherjee, A., 1970, "Metamorphic" and "metamorphosed" sulfide deposits: Econ. Geol. v. 65, p.886-889.

——1976, Ores and metamorphism: temporal and genetic relationships; *in* K.H. Wolf (ed.), Handbook of stratabound and stratiform ore deposits, v. 4: Elsevier, Amsterdam, p.203-260.

Naldrett, A.J., 1969, A portion of the system Fe-S-O between 900° and 1080 °C and its application to ore magmas: Jour. Petrology v. 10, p. 171-201.

——1971, Archaean ultramafic rocks: Publication of the Earth Physics Branch Ottawa, b. 42, p. 141-151.

——1973, Nickel sulphide deposits — their classification and genesis, with special emphasis on deposits of volcanic association: Trans. Can. Inst. Min. Metall. v. 76, p.183-201.

——1979, IGCP Project No. 161 and a proposed classification of Ni-Cu-PGE sulfide deposits: Canadian Mineralogist v. 17, p.143.

Naldrett, A.J., and Cabri, L.J., 1976, Ultramafic and related mafic rocks, their classification and genesis with special reference to the concentration of nickel sulfides and platinum-group elements: Econ. Geol. v. 71, p. 1131-1158.

Naldrett, A.J., and Turner, A.R., 1977, The geology and petrogenesis of a greenstone belt and related nickel sulphide mineralization at Yakabindie, Western Australia: Precambrian Res. v. 5, p.43-103.

Naldrett, A.J., Hoffman, E.L., Green, A.H., Chen-Lin Chou, Naldret, S.R., and Alcock, R.A., 1979, The composition of Ni-sulfides ores with particular reference to their content of PGE and Au: Canadian Mineralogist v. 17, p.403-415.

Nesbitt, R.W., 1971, Skeletal crystal forms in the ultramafic rocks of the Yilgarn Block, Western Australia: evidence for an Archean ultramafic liquid: Geol. Soc. Australia Special Pub. 3, p.331-347.

Nesbitt, R.W., and Sun, S.S., 1976, Geochemistry of Archaean spinifex-textured peridotites and peridotites and magnesian and low-magnesian tholeiites: Earth Planetary Sci. Letters v. 31, p.433-453.

Nesbitt, R.W., Sun, S.S., and Purvis, A.C., 1979, Komatiites: geochemistry and genesis: Canadian Mineralogist v. 17, p.165-186.

Nevill, M.W., 1974, The geology and mineralization of the Corkwood Prospect area, Lamboo Complex, East Kimberley, Western Australia: Univ. West Australia B.Sc. Hons thesis (unpublished).

Nevill, M.W., and Randell, J.P., 1975, McMahon Deeps Fe-Ni sulphide mineralization, progress report October, 1975, Kambalda Nickel Operations: Western Mining Corporation Ltd (unpublished report K2123).

Nickel, E.H., and Bridge, P.J., 1975, A garnierite with a high nickel content from Western Australia: Mineralogical Mag. v. 40, p.65-69.

Nickel, E.H. and Thornber, M.R., 1977, Chemical constraints on the weathering of serpentinites containing nickel-iron sulphides: Journ. Geochem. Exploration v. 8, p.235-245.

Nickel, E.H., Allchurch, P.D., Mason, M.G., and Wilmshurst, J.R., 1977, Supergene alteration at the Perseverance nickel deposit, Agnew, Western Australia: Econ. Geol. v.72, p.184-203.

Nickel, E.H., Hallberg, J.A., and Halligan, R., 1979, Unusual nickel mineralization at Nullagine, Western Australia: Geol. Soc. Australia Jour. v. 26, p.61-71.

Nisbet, E.G., Bickle, M.J., and Martin, A., 1977, The mafic and ultramafic lavas of the Belingwe greenstone belt, Rhodesia: Jour. Petrology v. 18, p. 521-566.

Noakes, L.C., and Jones, H.A., 1975, Mineral resources offshore; *in* C.L. Knight (ed.), Economic Geology of Australia and Papua New Guinea, Metals: Australasian Inst. Mining Metall. Mon. 5, p. 1093-1104.

O'Driscoll, E.S.T., 1971, The tectonic pattern of the nickel province of southwestern Australia: Soc. Mining Geol. Japan Spec. Issue 3, p. 23-33.

Oliver, R.L., Nesbitt, R.W., Hansen, D.M., and Franzen, N., 1972 Metamorphic olivine in ultramafic rocks from Western Australia: Contributions to Mineralogy and Petrology v. 36, p.335-342.

O'Meara, A.E. 1979, Concentrating, smelting and refining; *in* R.T. Prider (ed.), Mining in Western Australia: Univ. West. Australia Press, Perth, p.246-273.

Oversby, V.M., 1975, Lead isotope systematics and ages of Archaean acid intrusives in the Kalgoorlie-Norseman area, Western Australia: Geochim. et Cosmochim. Acta v. 39, p. 1107-1125.

Page, R.W., 1976, Reinterpretation of isotopic ages from the Halls Creek Mobile Zone, northwestern Australia: Australia Bur. Mineral Resources Jour. Australian Geol. Geophys. v. 1, p.79-81.

Palmer, A.J., 1973, The development of trackless mining at Kambalda: Australasian Inst. Mining Metall., Papers West Australia Conference 1983, Perth, p.331-337.

Papunen, H., Hakli, T.A., and Idman, H., 1979, Geological, geochemical and mineralogical features of sulfide-bearing ultramafic rocks in Finland: Canadian Mineralogist v. 17, p.217-232.

Peredery, W.V., 1979, Relationship of ultramafic amphibolites to metavolcanic rocks and serpentinites in the Thompson belt, Manitoba: Canadian Mineralogist v. 17, p.187-200.

Pettijohn, F.J., 1963, Data of geochemistry. S- Chemical composition of sandstones — excluding carbonate and volcanic sands: U.S. Geol. Survey Prof. Paper 440-S, 21 pp.

Platt, J.P. Allchurch, P.D., and Rutland, R.W.R., 1978, Archaean tectonics in the Agnew supracrustal belt: Precambrian Res. v. 7, p.3-30.

Prinz, M., 1967, Geochemistry of basaltic rocks: trace elements; *in* H.H. Hess and A. Poldervaart, (eds), Basalts: Interscience, New York, p.271-325.

Purvis, A.C., 1978, The geochemistry and metamorphic petrology of the Southern Cross — Forrestania greenstone belt at Digger Rocks, Western Australia: Univ. Adelaide Ph.D. thesis (unpublished).

Purvis, A.C., Nesbitt, R.W., and Hallberg, J.A., 1972, The geology of part of the Carr Boyd Rocks complex and its associated nickel mineralization: Econ. Geol. v. 67, p.1093-1113.

Pyke, D.R., Naldrett, A.J., and Eckstrand, O.R., 1973, Archaean ultramafic flows in Munro Township, Ontario: Geol. Soc. America Bull. v. 84, p.955-978.

Quick, D.R., 1978, Gibb shoot Kambalda Nickel Operations progress report, June 1978: Western Mining Corporation Ltd (unpublished report K2377).

Rajamani, V., and Naldrett, A.J., 1978, Partitioning of Fe, Co, Ni and Cu between sulfide liquid and basaltic melts and the composition of Ni-Cu sulfide deposits: Econ. Geol. v. 73, p. 82-93.

Ramsden, A.R., 1975, Compositions of co-existing pyrrhotites, pentlandites and pyrites at Spargoville, Western Australia: Canadian Mineralogist v. 13, p.133-137.

Randell, J., 1975, Geology of Durkin North ore environment: Kambalda Nickel Operations progress report, October 1975: Western Mining Corporation Ltd (unpublished report).

Reeve, J.S., 1975, The geology of Ken Shoot, Kambalda Nickel Operations; Western Mining Corporation Ltd (unpublished report K2165).

——1975a, Orebodies of the Otter Trough: Loreto and Gordon Shoots, progress report, Kambalda Nickel Operations: Western Mining Corporation Ltd (unpublished report K2155).

Reeve, J.S., 1977, The geology of Gibb Shoot and Long Shoot: Kambalda Nickel Operations Progress Report, April 1977: Western Mining Corporation Ltd (unpublished report K2256).

Richardson, B.D., 1976, The geology of the Radio Hill layered intrusion: Univ. West. Australia B.Sc. Hons thesis (unpublished).

Roberts, J.B., 1975, Windarra nickel deposits; *in* C. L. Knight, (ed.), Economic Geology of Australia and Papua New Guinea, Metals: Australasian Inst. Mining Metall. Mon. 5, p.129-143.

Robinson, K., 1976, Mount Hope area, Forrestania, Western Australia, final report — August 1976: Amax Exploration (Australia) Inc. (unpublished report) M1584.

Robinson, W.B., Stock, E.C., and Wright, R., 1973, The discovery and evaluation of the Windarra nickel deposit, Western Australia: Australasian Inst. Mining metall., Papers West. Australia Conference 1973, Perth, p.69-89.

Ross, J.R., 1974, Archaean nickel sulfide mineralization, Lunnon Shoot, Kambalda, Western Australia: Univ. California, Berkeley, Ph.D. thesis (unpublished).

Ross, J.R., and Hopkins, G.M.F., 1975, Kambalda nickel sulphide deposits; *in* C.L. Knight (ed.), Economic Geology of Australia and Papua New Guinea, Metals: Australasian Inst. Mining Metall. Mon. 5, p.100-121.

Ross, J.R., and Keays, R.R., 1979, Precious metals in volcanic-type nickel sulfide deposits in Western Australia. Part I: Relationship with the composition of the ores and their host rocks: Canadian Mineralogist v 17, p.417-435.

Ryan, G.R., 1966, Roebourne, Western Australia: West Australia Geol Survey 1:250 000 Geol. Series Explan. Notes.

Sands, D.G., 1978, Eucalyptus final report: Australian Selection (Pty) Ltd (unpublished report) M254.

Santul, J., 1975, The geology, geochemistry and mineralization of the south Windarra nickel ore deposit, W.A.: Univ. Adelaide B.Sc. Hons thesis (unpublished).

Sato, H., 1977, Nickel content of basaltic magmas; identification of primary magmas and a measure of the degree of olivine fractionation: Lithos v. 10, p.113-120.

Schmulian, M.L., 1975, Fisher shoot, progress report, October 1975, Kambalda Nickel Operations: Western Mining Corporation Ltd (unpublished report K2106).

Schmulian, M.L. 1982, The Windarra nickel deposits; *in* D.I. Groves and C.M. Lesher (eds.), Regional geology and nickel deposits of the Norseman-Wiluna belt, Excursion Guide for the Nickel Sulphide field conference III, Western Australia: Geology Department and Extension Service Univ. West. Australia Pub. 7.

Schultz, K., 1975, Carr-Boyd Rocks nickel-copper deposits: *in* C.L. Knight (ed.), Economic Geology of Australia and Papua New Guinea, Metals: Australasian Inst. Mining Metall. Mon. 5, p.125-128.

Schwabe, M., 1972, Cowarna Rocks, summary report: Great Boulder Mines Ltd (unpublished report) M1484.

Schwann, P.B., 1979, The geology of the Linger and Die pits, cobalt laterite operation: Western Mining Corporation Ltd (unpublished report K2180).

Seccombe, P.K., Groves, D.I., Binns, R.A., and Smith, J.W., 1978, A sulphur isotope study to test a genetic model for Fe-Ni sulphide mineralization at Mt Windarra, Western Australia; *in* B.W. Robinson (ed.), Stable isotopes in the earth Sciences: New Zealand Dept Sci. Indust. Research Bull. 220, p.187-200.

Segnit, E.R., 1976, Nickel slags from the flash smelter at Kalgoorlie, Western Australia: Australasian Inst. Mining Metall. Proc. v. 259, p. 37-44.

Shackleton, M.S., 1972, The geology of part of a greenstone belt at Bardoc, Western Australia: Univ. West. Australia B.Sc. Hons thesis (unpublished).

Sharpe, E.N., 1978, Hunt shoot: Progress report, August 1978, Kambalda Nickel Operations: Western Mining Corporation Ltd (unpublished report K2388).

Sheppy, N.R., 1979, Bremer Range project, annual report for 1978: Amoco Minerals Australia (unpublished report) M2262.

Sheppy, N.R., and Rowe, J., 1975, Nepean nickel deposit: *in* C.L. Knight (ed.), Economic Geology of Australia and Papua New Guinea, Metals: Australasian Inst. Mining Metall. Mon. 5, p.91-98.

Shewman, R.W., and Clark, L.A., 1970, Pentlandite phase relations in the Fe-Ni-S system and notes on the mono-sulfide solid solution: Canadian Jour. Earth Sciences v.7, p.67-85.

Shima, H., and Naldrett, A.J., 1975, Solubility of sulfur in an ultramafic melt and the relevance of the system Fe-S-O: Econ. Geol. v. 70, p.960-967.

Smith, B.H., 1977, Some aspects of the use of geochemistry in the search for nickel sulphides in lateritic terrain in Western Australia: Jour. Geochem. Exploration v. 8, p.259-281.

Sofoulis, J., 1966, Widgiemooltha, W.A.: West. Australia Geol. Survey 1:250 000 Series Explan. Notes.

Sprigg, R.C., and Rochow, K., 1975, Nickeliferous ochres in the Hinckley (W.A.) and Tomlinson (S.A.) Ranges ("Daisy Bates" — Wingelinna field); *in* C.L. Knight (ed.), Economic Geology of Australia and Papua New Guinea, Metals: Australasian Inst. Mining Metall. Mon. 5, p. 1008-1009.

Streckeisen, A., 1973, Classification and nomenclature of plutonic rocks, recommendations by the IUGS subcommission on the systematics of igneous rocks: Neues Jahrb. Mineralogie Monatsh. v. 4, p.149-164.

Sun, S.S., and Nesbitt, R.W., 1978, Petrogenesis of Archaean ultrabasic and basic volcanics: evidence from rare earth elements: Contributions to Mineralogy and Petrology v. 65, p.301-325.

Sykes, T., 1978, The money miners: Wildcat Press, Sydney.

Taylor, A.P., 1975, Textures in sulphide-bearing Archaean ultramafic rocks from the Spargoville area, Western Australia; *in* W.J. Verwoerd (ed.), Mineralization in Metamorphic Terrains: Geol. Soc. South Africa, 16th Congress, Stellenbosch, 1975, p.491-508.

Taylor, S.R., 1965, The application of trace element data to problems in petrology; *in* L.H. Ahrens, F. Press, S.K. Runcorn and H.C. Urey (eds), Physics and Chemistry of the Earth v.6: Pergamon, London, p.133-213.

——1969, Trace element chemistry of andesites and associated calc-alkaline rocks: Proc. Andesite Conf. Oregon Dep. Geol. Min. Ind. Bull. 65.

Thom, J.H., 1975, Kimberley Region; *in* Geology of Western Australia: West. Australia Geol. Survey Mem. 2, p.160-193.

Thom, R., and Barnes, R.G., 1977, Leonora, W.A.: West Australia Geol. Survey 1:250 000 Geol. Series Explan. Notes.

Thom, R., Lipple, S.L., and Sanders, C.C., 1977, Explanatory Notes Ravensthorpe, W.A. 1:250 000 Geological Sheet: Australia Bur. Mineral Resources.

Thornber, M.R., 1972, Pyrrhotite — the matrix of nickel sulphide mineralization: Australasian Inst. Mining Metall., Papers Newcastle Conference, 1972, p.51-58.

——1975, Supergene alteration of sulphides, I. A chemical model based on massive nickel sulphide deposits at Kambalda, Western Australia: Chemical Geology v. 15, p. 1-14.

Thornett, J.R., 1981, The Sally Malay deposit: gabbroid-associated nickel-copper sulfide mineralization in the Halls Creek mobile belt, Western Australia: Econ. Geol. v. 76 p.1565-1580.

Tomich, B.N.V., 1974, The geology and nickel mineralisation of the Ruth Well area, Western Australia: Univ. West. Australia B.Sc. Hons thesis (unpublished).

Travis, G.A., 1975, Mount Clifford nickel deposit; *in* C.L. Knight (ed.), Economic Geology of Australia and Papua New Guinea, Metals: Australasian Inst. Mining Metall, Mon. 5, p.144-146.

——1975a, Nickel-copper sulphide mineralization in the Jimberlana intrusion; *in* C.L. Knight (ed.), Economic Geology of Australia and Papua New Guinea, Metals: Australasian Inst. Mining Metall. Mon. 5, p.75-78.

Travis, G.A., Keays, R.R., and Davison, R.M., 1976, Palladium and iridium in the evaluation of nickel gossans in Western Australia: Econ. Geol. v. 71, p.1229-1243.

Travis, G.A., Fletcher, C.I., and Page, M.L., 1976a, Scotia East prospect, mineral claims 308W-321W, 324W, 325W, 244X, 245X, Annual reports to 29/6 /1976: Western Mining Corporation Ltd. (unpublished report) M1466.

Turek, A., and Compston, W., 1971, Rubidium-strontium geochronology in the Kalgoorlie region: Geol. Soc. Australia Special Publication 3, p.72.

Turekian, K.K., and Wedepohl, K.H., 1961, Distribution of the elements in some major units of the Earth's crust: Geol. Soc. America Bull. v. 72, p.175-192.

Turner, A.R., 1976, Wannaway No. 1 prospect, geological appraisal and ore resource assessment: Anaconda Australia Inc. M120 (unpublished report) M120.

Turner, A.R., and Ranford, L.C., 1975, Six mile nickel prospect; *in* C.L. Knight (ed.), Economic Geology of Australia and Papua New Guinea, Metals: Australasian Inst. Mining Metall. Mon. 5, p.156-159.

Tyrer, M., 1974, The geology, structure and mineralization of the Trough Well prospect, Yilgarn Goldfield, Western Australia: Univ. West. Australia B.Sc. Hons thesis (unpublished).

Tyrwhitt, D.S., and Orridge, E.R., 1975, Regional geology and mineralization of the Fraser Range Orogenic Belt, Western Australia; *in* C.L. Knight (ed.), Economic Geology of Australia and Papua New Guinea, Metals: Australasian Inst. Mining Metall. Mon. 5, p.405-408.

United States Bureau of Mines, 1975, Mineral facts and problems: U.S. Bureau Mines Bull. 667.

Uren, B.J., 1975, Murrin project; progress report March 1975: Northern Selcast (Pty) Ltd (unpublished report) M251.

Viljoen, M.J., and Viljoen, R.P., 1969, The geology and geochemistry of the Lower Ultramafic unit of the Onverwacht Group and a proposed new class of igneous rocks: Geol. Soc. South Africa Special Publication 2, p.55-85.

Vinogradov, A.P., 1962, Average contents of chemical elements in the principal types of igneous rocks of the Earth's crust: Geochimyka v. 7, p.641-644.

Wager, L.R., and Brown, G.M., 1967, Layered Igneous Rocks: Freeman, San Francisco, 588 pp.

Watchman, A.L., 1971, A study of two geochemical sections and the petrology and geochemistry of the ultramafic rocks, Mount Windarra orebody, Western Australia: Univ. Adelaide B.Sc. Hons thesis (unpublished).

Watmuff, I.G., 1974, Supergene alteration of the Mount Windarra nickel sulphide ore deposit, Western Australia: Mineralium Deposita v. 9, p.199-211.

Weaver, B.L., and Tarney, J., 1979, Thermal aspects of komatiite generation and greenstone belt models: Nature v. 279, p.689-692.

Whitfield, G.B., 1973, Geochemistry of alteration of Archaean layered sills in Western Australia: Univ. West. Australia M.Sc. thesis (unpublished).

Wilde, S.A., 1982, Explanatory notes on Pemberton 1:250 000 Geological Sheet, W.A.: West Australia Geol. Survey Rec. 1981/10.

Wilding, I.G.P., 1980, Corkwood Cu:Ni prospect, Kimberleys, W.A.; *in* C.R.M. Butt and R.E. Smith (eds.), Conceptual Models in Exploration Geochemistry — Australia: J. Geochem. Exploration v. 12, p. 220-224.

Willett, G., Eshuys, E., and Guy, B., 1978 Ultramafic rocks of the Widgiemooltha-Norseman area, Western Australia: petrological diversity, geochemistry and mineralization: Precambrian Res. v. 6, p. 133-156.

Williams, D.A.C., 1971, Determination of primary mineralogy and textures in ultramafic rocks from Mt Monger, Western Australia: Geol. Soc. Australia Special Publication 3, p.259-268.

——1972, Archaean ultramafic, mafic and associated rocks, Mt Monger, Western Australia: Geol. Soc Australia Jour v. 19(2), p.163-188.

——1979, The association of some nickel sulfide deposits with komatiitic volcanism in Rhodesia: Canadian Mineralogist v. 17, p.337-349.

Williams, D.A.C., and Hallberg, J.A., 1973, Archaean layered intrusions of the Eastern Goldfields region, Western Australia: Contributions to Mineralogy and Petrology v. 38, p.45-70.

Williams, I.R., 1970, Explanatory Notes, Kurnalpi, W.A. 1:250 000 Geological sheet; Australia Bur. Mineral Resources.

——1974, Structural subdivision of the Eastern Goldfields Province, Yilgarn Block: West. Australia Geol. Survey Ann. Rept 1973, p.53-59.

——1976, Regional interpretation map of the Archaean geology, southeast part of the Yilgarn Block, 1:1 000 000 scale: Geol. Surv. West. Australia.

Williams, I.R., Brakel, A.T., Chin, R.J., and Williams, S.J., 1976, The stratigraphy of the eastern Bangemall Basin and the Paterson Province: West. Australia Geol. Survey Ann. Rept 1975, p.79-83.

Williams, I.R., Walker, I., and Hocking, R.M., 1980, Explanatory Notes on Byro 1:250 000 Geological Sheet, W.A.: West. Australia Geol. Survey Rec. 1980/5.

Williams, S.J., Williams, I.R., and Hocking, R.M., 1980, Explanatory notes on Glenburgh 1:250 000 Geological Sheet, W.A.: West. Australia Geol. Survey Rec. 1980/4.

Wilmshurst, J.R., 1975, The weathering of nickeliferous sulphides and their associated rocks in Western Australia: *in* I.L. Elliott and W.K. Fletcher (eds), Geochemical Exploration 1974, Developments in Economic Geology 1: Elsevier, Amsterdam, p.417-436.

Wilson, H.D.B., Kilburn, L.C., Graham, A.R., and Ramlal, K., 1969, Geochemistry of some Canadian nickeliferous ultrabasic intrusions; *in* H.D.B. Wilson, (ed.), Magmatic ore deposits: Economic Geology Mon. 4, p. 294-309.

Witt, W.K., 1972, Geology and sulphide mineralization at Forrestania, Western Australia: Univ. West Australia B.Sc. Hons thesis (unpublished).

Wolff, G.C. 1977, Redross mine, final report — 1977 exploration program: Anaconda Australia Inc. (Mining Division) (unpublished report) M120.

Woodall, R., 1965, Structure of the Kalgoorlie Goldfield; *in* J. McAndrew (ed.), Geology of Australian ore deposits: Eight Commonwealth Mining and Metall. Cong. Australia and New Zealand, 1965, v.1, p.71-79.

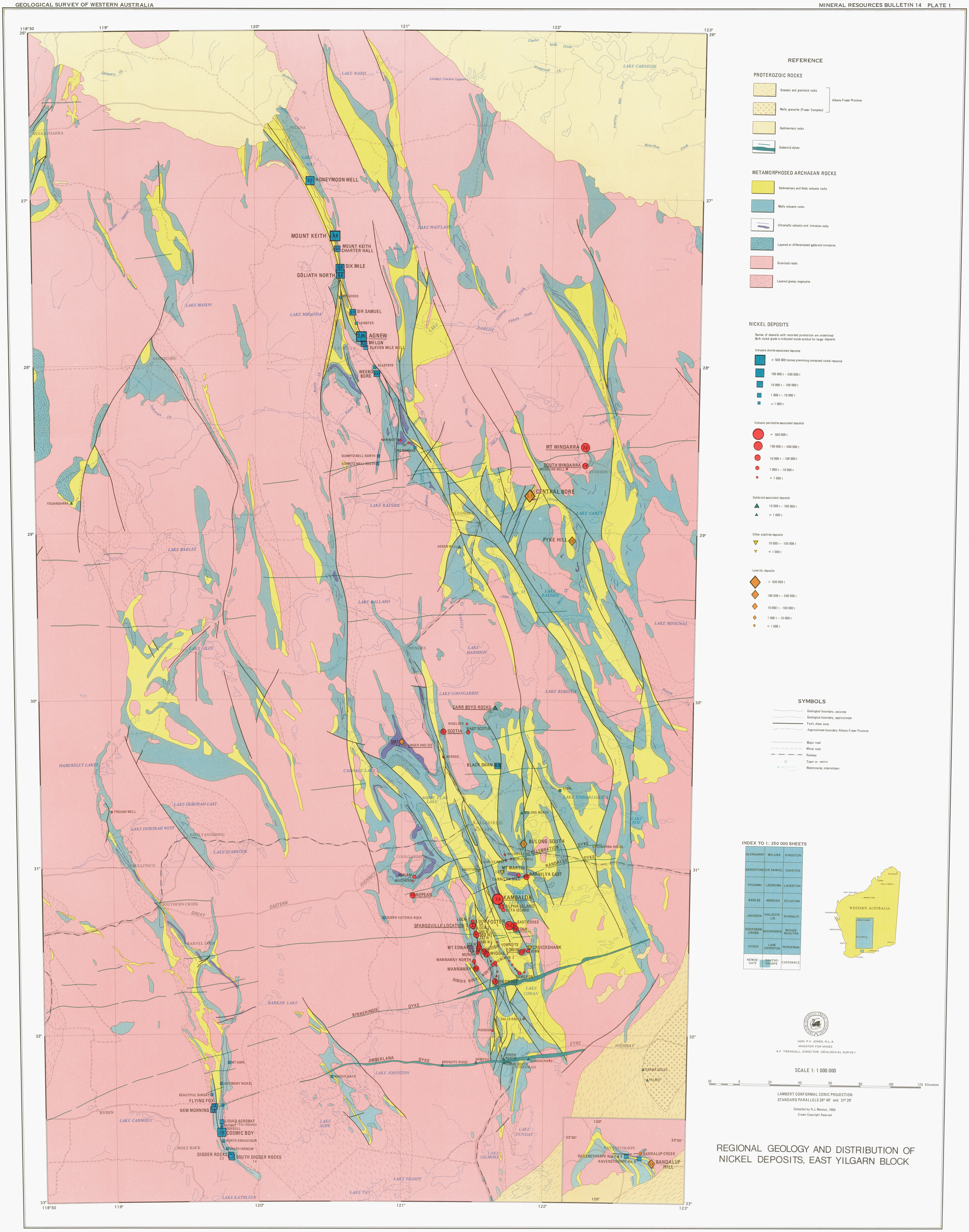
——1974, Nickel resources of Australia: Paper presented at Circum-Pacific Energy and Minerals Resources Conference, August, Honolulu.

Woodall, R., and Travis, G.A., 1969, The Kambalda nickel deposits, Western Australia: Ninth Commonwealth Mining Metall. Cong. 1969, London, v.2, p.517-533.

Woolrich, P., and Giorgetta, N., 1978, The mineralogy and geochemistry of the iron-nickel sulphides at Kambalda: Western Mining Corporation Ltd (unpublished report K2379).

INDEX

The suffix (F) or (T) indicates that the reference is to a Figure or Table appearing on that page.


REFERENCE
PROTEROZOIC ROCKS
Gneissic and granitoid rocks
Mafic granulite (Fraser Complex)
Albany-Fraser Province
Sedimentary rocks
Gabbroid dykes
METAMORPHOSED ARCHAEAN ROCKS
Sedimentary and felsic volcanic rocks
Mafic volcanic rocks
Ultramafic volcanic and intrusive rocks
Layered or differentiated gabbroid intrusions
Granitoid rocks
Layered gneiss; migmatite
NICKEL DEPOSITS
Names of deposits with recorded production are underlined
Bulk nickel grade is indicated inside symbol for larger deposits
Intrusive dunite-associated deposits
> 500 000 tonnes premining contained nickel resource
100 000 t – 500 000 t
10 000 t – 100 000 t
1 000 t – 10 000 t
< 1 000 t
Volcanic peridotite-associated deposits
> 500 000 t
100 000 t – 500 000 t
10 000 t – 100 000 t
1 000 t – 10 000 t
< 1 000 t
Gabbroid-associated deposits
10 000 t – 100 000 t
< 1 000 t
Other sulphide deposits
10 000 t – 100 000 t
< 1 000 t
Lateritic deposits
> 500 000 t
100 000 t – 500 000 t
10 000 t – 100 000 t
1 000 t – 10 000 t
< 1 000 t
SYMBOLS
Geological boundary, accurate
Geological boundary, approximate
Fault, shear zone
Approximate boundary Albany-Fraser Province
Major road
Minor road
Railway
Town or centre
Watercourse, intermittent
INDEX TO 1 : 250 000 SHEETS
GLENGARRY
WILUNA
KINGSTON
SANDSTONE
SIR SAMUEL
DUKETON
YOUANMI
LEONORA
LAVERTON
BARLEE
MENZIES
EDJUDINA
JACKSON
KALGOORLIE
KURNALPI
SOUTHERN CROSS
BOORABBIN
WIDGIEMOOLTHA
HYDEN
LAKE JOHNSTON
NORSEMAN
NEWDEGATE
RAVENSTHORPE
ESPERANCE
WESTERN AUSTRALIA
HON. P.V. JONES, M.L.A.
MINISTER FOR MINES
A.F. TRENDALL, DIRECTOR, GEOLOGICAL SURVEY
SCALE 1 : 1 000 000
20 0 20 40 60 80 100 120 Kilometres
LAMBERT CONFORMAL CONIC PROJECTION
STANDARD PARALLELS 28° 40' and 31° 20'
Compiled by R.J. Marston, 1980
Crown Copyright Reserved
REGIONAL GEOLOGY AND DISTRIBUTION OF NICKEL DEPOSITS, EAST YILGARN BLOCK
HONEYMOON WELL
MOUNT KEITH
MOUNT KEITH CHARTER HALL
SIX MILE
GOLIATH NORTH
SIR SAMUEL
AGNEW
MELON
ELEVEN MILE WELL
WEEBO BORE
MT WINDARRA
SOUTH WINDARRA
CENTRAL BORE
PYKE HILL
CARR BOYD ROCKS
SCOTIA
BLACK SWAN
BULONG SOUTH
MT MARTIN
CARNILYA EAST
KAMBALDA
NEPEAN
FOSTER
SPARGOVILLE LOCATION 5
MT EDWARDS
WIDGIESMOOLTHA
CRUICKSHANK
WANNAWAY
REDROSS
BINNERINGIE DYKE
JIMBERLANA DYKE
FLYING FOX
NEW MORNING
COSMIC BOY
DIGGER ROCKS
SOUTH DIGGER ROCKS
BANDALUP CREEK
BANDALUP HILL
RAVENSTHORPE
LAKE CARNEGIE
LAKE WAY
LAKE MAITLAND
LAKE MASON
LAKE MIRANDA
LAKE DARLOT
LAKE RAESIDE
LAKE CAREY
LAKE BARLEE
LAKE BALLARD
LAKE MINIGWAL
LAKE GILES
LAKE MARMION
LAKE REBECCA
LAKE GOONGARRIE
HAMERSLEY LAKES
CARNAGE LAKE
LAKE DEBORAH EAST
LAKE DEBORAH WEST
LAKE SEABROOK
LAKE YINDARLGOODA
LAKE ROE
LAKE COWAN
BARKER LAKE
LAKE JOHNSTON
LAKE CARMODY
LAKE HOPE
LAKE DUNDAS
LAKE GILMORE
LAKE SHARPE
LAKE TAY
LAKE KATHLEEN
WILUNA
LEONORA
LAVERTON
MENZIES
KALGOORLIE
BOULDER
COOLGARDIE
SOUTHERN CROSS
NORSEMAN
HYDEN
EYRE HIGHWAY
GREAT EASTERN HIGHWAY

CROSS SECTIONS DRAWN THROUGH VARIOUS PARTS OF THE KAMBALDA DOME

Interpretation of traverse diamond drilling by geologists of Western Mining Corporation Limited

NOTE: HORIZONTAL AND VERTICAL SCALES ARE EQUAL FOR ALL SECTIONS