GEOLOGICAL SURVEY OF WESTERN AUSTRALIA

MINERAL RESOURCES BULLETIN 13

COPPER MINERALIZATION

IN

WESTERN AUSTRALIA

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by

R. J. MARSTON

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PREFATORY NOTE

Western Australia has never been a major producer of copper in the national context, but copper deposits are abundant and occur in many different forms and geological terrains. Despite the unstable nature of the international copper market, exploration interest has remained high. In the last decade this has resulted in the discovery of several important, small to medium-sized deposits in the Murchison, Northeastern Goldfields, Pilbara and East Kimberley regions. Zinc, lead, nickel, or molybdenum may accompany copper in such deposits.

The author has studied the State's copper mineralization and resources by inspecting all important deposits and the majority of the remainder, and by supplementary laboratory petrological examinations. Data resulting from this work have been combined with published data and information provided by mining companies to give an account of each deposit and its geological setting. Deposits have been classified into various types using factual data only, thereby allowing the reader to make an independent genetic interpretation if desired.

This is the second Mineral Resources Bulletin dealing with copper. The great advances made in understanding the geology of the State over the last 15 years coupled with a surge in base metal exploration, have made possible what amounts to considerably more in volume and scope than simply a revision of the first bulletin published in 1963. In 1973 to 1975 A.A. Gibson began collecting material for the current bulletin. However, the bulk of the work was completed in 1976 to 1977 by the author.

It is considered that this bulletin will be an essential reference for anyone interested in exploration or prospecting for copper in this State.

1 June 1978.

J. H. Lord,
Director.

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CHAPTER 1

Introduction

CONSTRUCTION OF BULLETIN

OBJECT AND SCOPE

This bulletin reports the results of a study of cupriferous mineralization in Western Australia undertaken by the writer in the period 1976 to mid-1977. The object of the study is to summarize available information and to assess, where possible, the economic potential of abandoned mines, prospects, and occurrences, in which copper remains the metal of major commercial interest.

The bulletin is not concerned with deposits of other metal in which copper is present in uneconomic amounts, although gold and lead-zinc mines in this category are listed in Appendices 2 and 3. Most nickel deposits contain economically recoverable amounts of copper; however these deposits are not described in detail except where copper exceeds nickel in amount in average ore grades. A bulletin dealing with nickel mineralization in the State is in preparation.

SOURCES OF INFORMATION

The information presented has been compiled from published sources, unpublished reports of mining companies, 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 including pace and compass surveys made by the writer in 1976. Data contained in an earlier Mineral Resources Bulletin (Low, 1963) on copper has been revised and incorporated where appropriate. Information derived from field inspections and company reports represents the major advance in data accumulation since Low (1963) compiled the previous bulletin. Great advances in knowledge of the regional geology of the State have been made in the last 15 years (Geological Survey of Western Australia, 1975). This new knowledge, coupled with the information derived from the subsurface testing of many formerly producing centres as well as new prospects by modern exploration methods, allows a fuller and more accurate assessment of cupriferous mineralization to be made than was possible in Low's time. More specifically this permits mineralization to be grouped under geologically meaningful headings rather than gazetted goldfields and mineral fields.

LAYOUT

The first two chapters of the bulletin provide general and historical information, and a brief account of the characteristics of copper as a component of the earth's crust. Chapter 3 sets the scene for the remainder of the work by describing: (i) the tectonic provinces of the State, and (ii) the types of mineralization encountered in these provinces. Thus classification is by lithology and structure at two orders of magnitude: the regional scale, and the local scale. The lithology and geometry of the host-rock units are used at the local scale, thereby avoiding potentially misleading classifications based on debatable criteria of ore genesis. This subdivision into types of mineralization is followed in succeeding chapters except where numerous small occurrences have been grouped for convenience of description. The economic potential for commercially important copper mineralization is discussed on a statewide basis at the end of Chapter 3, and for each tectonic province in the opening section entitled *Summary and Conclusions*. Descriptions of mineralization are arranged in chapters by tectonic province starting in the northern part of the State and progressing southwards. Details given in Low (1963) of production statistics for each mine up to the end of 1960 are summarized and to them are added more recent data in a table for each tectonic province.

TERMINOLOGY AND ABBREVIATIONS

To avoid misunderstanding, many descriptive and genetic terms applied to ore deposits require definition because of loose usage in the past. The terms *stratabound* and *stratiform* are used here in a wider sense than that proposed by Stanton (1972, p.541); the definitions advanced by Canavan (1973) are adopted in modified form. Definitions of the terms *syngenetic, diagenetic, epigenetic, hydrothermal, hypogene* and *supergene* are slightly modified from Tourtelot and Vine (1976, pp. 2-3). Definitions of *resource* and *reserve* and qualifying terms are those used by the United States Bureau of Mines and Geological Survey (United States Geological Survey, 1976).

Stratabound: A deposit which is confined within a rock layer or group of layers at a large scale, whether composed of sedimentary or igneous rock, including metamorphic rocks in which primary layering can be identified is stratabound. The ore may have any form of distribution, disseminated in, concordant with, or even transgressive to, the layering on a small scale.

Stratiform: A (stratabound) deposit which has the form of a layer and which occurs within and is strictly conformable with the stratification or layering of enclosing sedimentary, metamorphic, or igneous rocks is stratiform.

Syngenetic: Minerals deposited or formed simultaneously with the enclosing sediment or igneous rock are syngenetic.

Diagenetic: The post-depositional formation of new minerals by equilibrium reactions between the original sedimentary rock constituents, both detrital and chemical, and interstitial fluids and gases from within the sequence is said to be diagenetic. By implication, the elements making up the new minerals were present in the sedimentary sequence at the time of deposition.

Epigenetic: The post-depositional formation of new minerals, especially ore minerals, by chemical reactions between original sedimentary rock constituents and solutions from an external source is said to be epigenetic. The solutions may be of juvenile, connate or meteoric origin.

Hydrothermal: Hot aqueous solutions, consisting of water derived from juvenile, connate or meteoric sources, or any combination of these sources are said to be hydrothermal.

Hypogene: Hypogene describes ascending solutions, generally in the form of volcanic exhalations or hydrothermal waters.

Supergene: Supergene describes descending solutions, generally meteoric water entering groundwater systems.

Resource: A concentration of naturally occurring solid, liquid, or gaseous materials in or on the earth's crust, in such form that economic extraction of a commodity is currently or potentially feasible, is a resource.

Reserve: That portion of the identified resource from which a usable mineral and energy commodity can be economically and legally extracted at the time of determination is a reserve. The term *ore* is used for reserves of some minerals.

The following terms are applied to reserves or resources that may become reserves as a result of changes in economic and legal conditions.

Measured: Those reserves or resources for which tonnage is computed from dimensions revealed in outcrops, trenches, workings and drill holes, and for which the grade is computed from the results of detailed sampling are classed as measured. The sites for inspection, sampling, and measurement are spaced so closely, and the geologic character is so well defined that size, shape, and mineral content are well established. The computed tonnage and grade are judged to be accurate within limits which are stated, and no such limit is judged to be different from the computed tonnage or grade by more than 20 per cent.

Indicated: Those reserves or resources for which tonnage and grade are computed partly from specific measurements, samples, or production data, and partly from projection for a reasonable distance on geological evidence are classed as indicated. The sites available for inspection, measurement, and sampling are too widely or otherwise inappropriately spaced to permit the mineral bodies to be outlined completely or the grade established throughout.

Demonstrated: Demonstrated is a collective term for the sum of measured and indicated reserves or resources.

Inferred: Inferred reserves or resources are those for which quantitative estimates are based largely on broad knowledge of the geologic character of the deposit, and for which there are few, if any, samples or measurements. The estimates are based on an assumed continuity or repetition of which there is geologic evidence; this evidence may include comparison with deposits of similar type.

The following terms appear throughout the bulletin and are used in the sense as defined here.

Deposit: A concentration, above common crustal abundance levels, of naturally occurring minerals which contain elements of commercial value is a deposit.

Occurrence: A deposit whose small size and/or low level of mineral concentration render it of no current, or foreseeable potential, economic value is an occurrence.

Prospect: A deposit that has been tested to some degree by subsurface exploration is a prospect.

Mine: A deposit from which ore has been extracted is a mine.

Abbreviations used in this bulletin which require definition are listed below:

t	tonnes
m.y.	million years
M	million
G.M.L.	gold mining lease
L.T.T.	licence to treat tailings
M.C.	mineral claim
M.L.	mineral lease
P.A.	prospecting area
Sheet	1:250 000 map series area
T.R.	temporary reserve

Acmex	Acmex Holdings N.L.
BMC	Almagamet Australia Ltd formerly British Metal Corporation
Amad	Amad N.L.
Amax	Amax Exploration Australia Inc. formerly Amax Mining Australia Inc
Amoco	Amoco Minerals Australia Co.
Anglo-Westralian	Anglo-Westralian Mining Pty Ltd
Aquitaine	Aquitaine Australia Minerals Pty Ltd
Asarco	Asarco (Aust) Pty Ltd
Anglo American	Australian Anglo American Services Ltd formerly Anglo American Corporation Ltd
ACM	Australian Consolidated Minerals N.L.
Selco	Australian Selection (Proprietary) Ltd
Carpentaria	Carpentaria Exploration Company Pty Ltd
Carr Boyd	Carr Boyd Minerals
Cominco	Cominco Exploration Pty Ltd
Gold Fields	Consolidated Gold Fields Australia Ltd
Conwest	Conwest (Aust) N.L.
CRA	Conzinc Riotinto of Australia Exploration Pty Ltd
Eastmet	Eastmet Minerals N.L.
EZ	Electrolytic Zinc Co. of Australasia Ltd
Endeavour	Endeavour Oil Co. N.L.
Esso	Esso Australia Ltd
Geometals	Geometals N.L.
Great Boulder	Great Boulder Mines Ltd
Group Explorations	Group Explorations Pty Ltd
Hawkstone	Hawkstone Investments Ltd formerly Hawkstone Minerals
Hollandia	Hollandia Ravensthorpe N.L.

INAL	International Nickel Australia Ltd
Kennco	Kennco Explorations (Australia) Pty Ltd formerly Kennecott Explorations (Australia) Pty Ltd
Metals Ex	Metals Exploration Ltd
Minefields	Minefields Exploration N.L.
Newmont	Newmont Pty Ltd
NGM	Norseman Gold Mines N.L.
N. Kalgurli	North Kalgurli Mines Ltd
Otter	Otter Exploration N.L.
Peko	Peko-Wallsend Ltd
PMI	Pickands Mather and Co. International
Placer	Placer Prospecting Pty Ltd
Planet	Planet Management and Research Pty Ltd
Poseidon	Poseidon Limited
Project Mining	Project Mining Corporation Ltd
Richenda	Richenda Minerals N.L.
Roebourne	Roebourne Exploration and Mining Ltd
Serem	Serem (Australia) Pty Ltd
Tanks	Tanganyika Holdings Ltd
Texasgulf	Texasgulf Australia Ltd
BHP	The Broken Hill Proprietary Co. Ltd
Unimin	Union Miniere Development and Mining Corporation Ltd
Utah	Utah Development Co.
Union Oil — Hanna — Homestake	Union Oil Development Corporation—Australian Hanna Ltd—Homestake Iron Ore Company of Australia Ltd
WMC	Western Mining Corporation Ltd
Westralian Nickel	Westralian Nickel Exploration N.L.
Whim Creek	Whim Creek Consolidated N.L.

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COPPER IN THE WORLD'S ECONOMY

PROPERTIES AND USES OF COPPER

The most important properties of copper are its (i) electrical and thermal conductivity, (ii) corrosion resistance, (iii) ductility and malleability, and (iv) mechanical strength, plus an ability to be alloyed readily with many other metals to produce materials with a wide range of properties. Copper can be easily welded, brazed and soldered, and has good electro-deposition characteristics. The metal is non-magnetic and has an attractive colour.

Since its birth in the mid-19th century the electrical industry has created a big demand for copper, and the industry has been responsible for about half of the total world consumption in recent times. Good conductivity, combined with ease of working and forming, make copper an ideal substance for wire and underground cable, which are made from wirebars, the most common product of modern refineries. The building industry is the second largest copper consumer; this consumption is based on the metal's corrosion resistance, thermal conductivity and ease of fabrication and jointing. Non-electrical industrial engineering usage, including the chemical industry, stems from the same properties, and consumes amounts of copper comparable with the building industry. With the addition of the fourth major consumer, the transport industry, which uses copper in motors, generators, communications systems, heaters radiators and many other items, about 90 per cent of the world's copper consumption is accounted for. Miscellaneous uses including coinage, munitions, copper salts for agricultural applications, domestic consumer goods and decorative items make up the remainder. The diverse properties of the metal have resulted in a very diverse usage. Aluminium shares some of the properties and a lower and more stable price, plus continuity of supply, have resulted in aluminium becoming a major alternative material to copper since 1950, particularly in the field of electrical conductivity. Plastics, stainless steel, and other ferrous metals are the other competitors of copper, largely in the building, chemical and transport industries.

PRODUCTION

The earliest records of copper smelting are found in the Timna valley in southern Israel and date from the fourth millenium B.C. Copper and tin minerals occur near one another in many parts of the world (for example Cornwall, southwest England), and the discovery of bronze, an alloy of about 88 per cent copper and 12 per cent tin, increased demand for copper. Roman civilization widened the use of copper further to include a new and cheaper alloy called brass made up of about 70 per cent copper and 30 per cent zinc. Cyprus supplied the bulk of the Romans' copper and the English word *copper* derives from the Latin name for the island—*Cyprium*. Production continued on a small scale, probably totalling no more than a few thousand tons of metal, until the industrial age began in Europe in the early 19th century. At this time three-quarters of the world's annual production of 16 000 t of metal came from Britain. By 1862 the figure was around 100 000 t, and Chile was the main producer of primary copper until the United States of America reached premier position in the mid-1880's.

New concepts of mass production of ore by open-pit methods, coupled with developments in the concentration of sulphides ores by flotation techniques, led, in the period 1905 to 1915, to the exploitation of giant, low-grade copper deposits—the 'porphyry coppers'—first in western North America, and then in

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Chile. In just 17 years, world primary copper production doubled from 1 Mt in 1912 to 2 Mt in 1929. Another 31 years brought the total to 4 Mt in 1960; the United States was still the major producer, but was now followed by the African 'Copperbelt' countries (Zaïre and Zambia), then Chile, the U.S.S.R., Canada, Peru, Australia, and Japan. World mine production in 1975 totalled 7.385 Mt of copper, a fall of 0.5 Mt on the 1974 figure. This resulted from cutbacks in production, mainly by U.S. producers and the CIPEC (Conseil Intergouvernmental des Pays Exportateurs de Cuivre) countries, which are now Chile, Indonesia, Peru, Zaïre, and Zambia. Australia, Papua-New Guinea, Yugoslavia and Mauritania are associate members of CIPEC. These cuts stemmed from reduced demand and low prices, which in turn were the result of a general economic recession. A rise in mine production, though not to the 1974 value, is likely for 1976.

Total Australian mine production to the end of 1975 is recorded as 4 466 436 t of contained copper. Production commenced in 1844 with the exploitation of supergene deposits at Kapunda and Burra in South Australia. Copper mining soon spread to other areas in this State (for example Wallaroo-Moonta producing in period 1860 to 1923), and to other states including the Claremont-Rockhampton region (producing from 1860 to 1914) in Queensland, and Cobar (commencing 1870) in New South Wales. In Western Australia exporting of copper ore from the Northampton Mineral Field probably began in 1853. At the close of the 19th century, two gold mines discovered in the 1880's—Mount Lyell in Tasmania and Mount Morgan in Queensland—began producing copper and have continued to do so until the present time. The two major copper mining areas in Western Australia, Ravensthorpe and Whim Creek, were discovered at the turn of the century, but they are of little significance as producers in the national context. Before the slump in demand and prices came at the end of the First World War, Australia was producing around 40 000 t of copper annually (Fig. 1). The recovery was slow, and it was not until 1942 that demands of the Second World War obliged the lead-zinc mine at Mount Isa to commence mining copper deposits (discovered earlier) that production rose above 30 000 t again. This was short lived, as early in 1946, in the face of falling copper prices and steeply rising lead prices, the company switched the treatment plant back to lead. However increased profits from lead mining allowed a new, separate treatment plant for copper to be built and, since Mount Isa resumed copper production in late 1952, the mine has dominated Australian copper statistics (Fig. 1). In 1953 Mount Isa contributed 43 per cent of the annual total (38 057 t) of copper produced in Australia, and by 1974 this proportion had increased to 65 per cent. In 1974 (annual total 251 340 t) other mines producing in excess of 6 000 tonnes of contained copper were (in decreasing order of importance): Mount Lyell, Tennant Creek (Northern Territory), Mount Morgan, Cobar, Kanmantoo (South Australia) and Mammoth (Queensland). Australian copper production in 1975 and 1976 was 13 per cent lower than the 1974 figures, and reflects the general downturn in the industry throughout the world. Production from the two major copper mines at Tennant Creek was suspended in February 1975, the Kanmantoo open pit mine was put on a care and maintenance basis in mid-1976, and the North Lyell mine was closed in an attempt to halt mounting losses in November 1976.

MARKETS AND PRICES

For the last 100 years supplies of new copper metal have been sold at prices related to quotations on a commodity exchange or at prices fixed by producers. The U.S.A. has been more or less self-sufficient in copper mining, smelting, refining and fabrication during this period, consequently the marketing of copper there can be excluded from world trade in the metal. The bulk of the world's mine production that is traded internationally is sold at prices based on quotations in pounds sterling at the London Metal Exchange (LME). The complexities of world trading in copper are discussed by Stewardson (1969) and Prain (1975).

In Australia the producer price of copper before the Second World War followed the LME quotation (Fig. 1). The LME was closed from 1939 to 1953, and from December 1939 until October 1954 Australian producer and consumer prices were controlled by the government although control in Queensland ceased a little earlier, in September 1952. During the period of government control, both imported and domestically produced copper was pooled. The producer and consumer prices were not always the same, the difference being accumulated or paid out of the 'Copper Price Equalisation Pool'. After control was lifted the Copper Producers Association of Australia set a monthly price based on average LME quotations plus freight and other charges, and this resulted in the domestic price being comparable to the landed cost of imported copper. The steep fall of prices in 1956-1957 (Fig. 1) brought government assistance from May 1957 in the form of a maintained landed cost for copper, plus a bounty paid on local sales, subject to a profit limitation of 10 per cent. The Copper Bounty Act and its amendments controlled the floor price of domestic copper until the end of 1966, although rising world prices in 1965 made the Act redundant.

Except for the period April 1965 to August 1966, when Australian producers' prices followed the lower figure of the LME versus a Zambian producers price, the domestic price of copper was based, until September 1974, on the LME spot price for electrolytic wirebar. This was in line with the practice of the other major copper exporting countries, Canada and the CIPEC group. When the Australian producers began

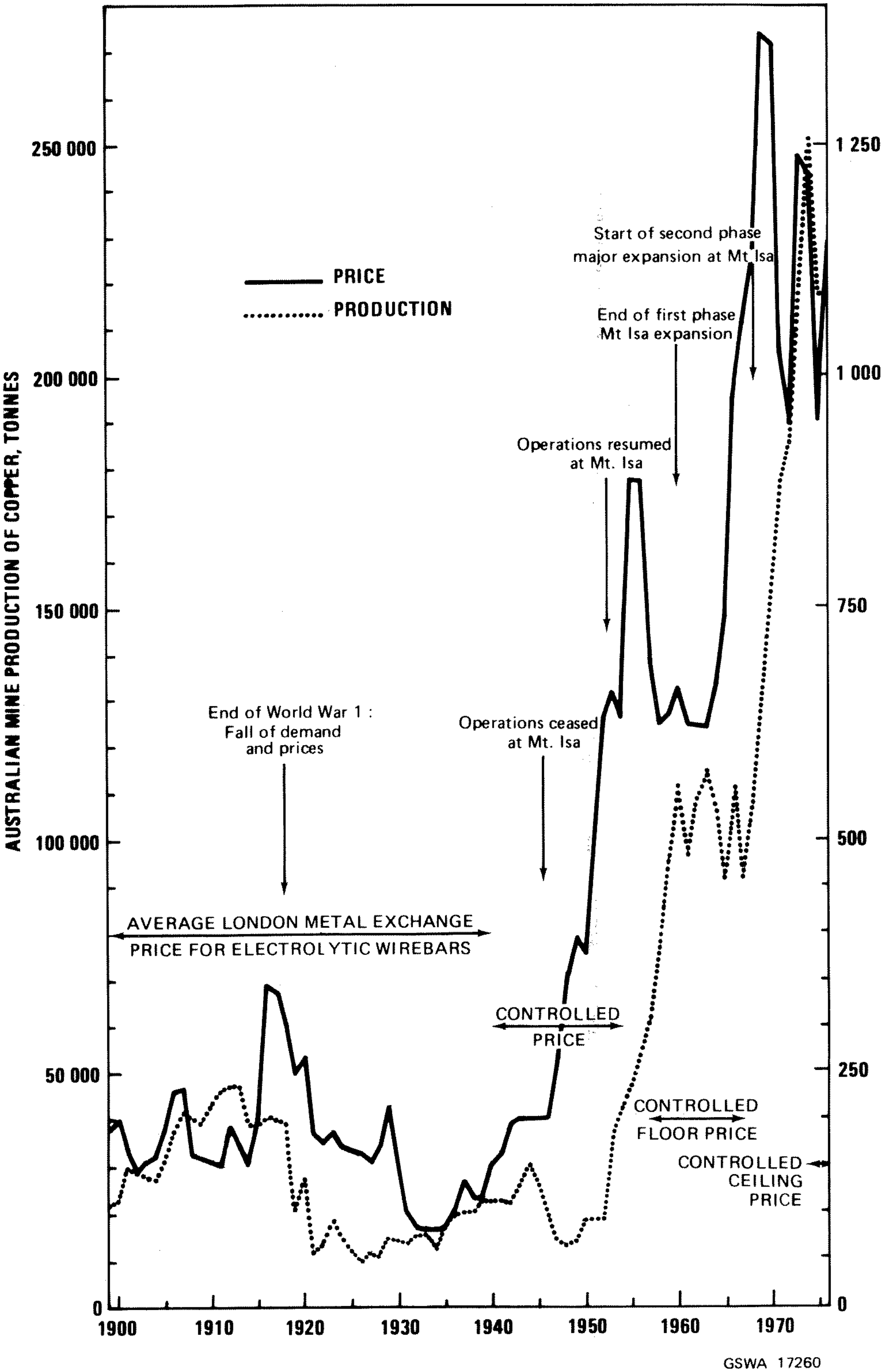

Figure 1. Price and mine production of copper in Australia 1899-1976

following the steeply rising London prices in 1974 a maximum domestic price of A$1 460 per tonne was set by the Prices Justification Tribunal (PJT).

This figure was exceeded by London prices in 1974 and again in mid-1976 after the slump in 1975. In response to a request by Mount Isa Mines Limited, the PJT freed copper prices in August 1976, but reserved its right to control prices again if a steep rise occurred. Changes to the method of relating prices to the LME quotations and to trading practices between producers and consumers in Australia were recommended by the PJT.

COPPER MINING IN WESTERN AUSTRALIA

HISTORY AND PRODUCTION

A comparison of Australian with Western Australian copper statistics (Figs. 1 and 2) shows that the State has never been a major contributor to the national totals. The total recorded production to the end of 1976 of contained copper from all sources for the State is 58 838 t (Tables 1, 2 and 3). Mines with recorded production are shown on Plate 1.

Productive copper mining in the State dates from 1856 when the Wanerenooka mine just north of Northampton was discovered, although several early official publications gives the date incorrectly as 1842 (see discussion in Blockley 1971b, pp. 15-16). The presence of copper as well as lead mineralization had been noted as early as 1851 in the Geraldine area at the northern tip of the Northampton Mineral Field. Statistics in Maitland (1903, p. 12) record the export of a very small amount of copper ore from the Northampton Mineral Field in 1853 and 1855, probably from the Geraldine and White Peak copper mines respectively. Mining of copper here continued sporadically until the turn of the century by which time ore with some 1 800 t of contained copper had been exported. The most productive period was from 1858 to 1867 (Fig. 2), when ore containing 1 127 t of copper, to which the Wheal Fortune mine was the biggest single contributor, was exported. The exodus of miners to the eastern Australian goldfields in the late 1860's caused the closure of many mines.

Discoveries of copper mineralization rapidly increased following the proclamation of the first goldfield in the State, the Kimberley Goldfield, on 20th May, 1886. Gold prospectors were attracted by showings of green and blue secondary copper minerals, but few deposits supported production of any importance. In the late 1880's copper was discovered in the West Pilbara region (then part of the Pilbara Goldfield as proclaimed on 8th July, 1889) firstly to the south of Roebourne (Carlow Castle area) and then east of Roebourne at Whim Creek. Simpson and Gibson (1907, p. 19) reported the discovery of copper and lead near Roebourne in 1872, but the reliability of this date is in doubt. Woodward (1890, p. 20) described the Whim Creek discovery as 'one of the largest and richest copper lodes in the Colony', and in fact the productivity of the deposit has only been exceeded by the Ravensthorpe district mines on the south coast. High operating costs and low prices, coupled with the lack of an economically feasible method of treating the large amounts of low-grade oxidized ore present, resulted in an erratic history of production for the Whim Creek mine. The major period of output was from 1909 to 1914, during which ore containing nearly 5 900 t of

TABLE 1. ANNUAL PRODUCTION OF COPPER ORE AND CONCENTRATES WESTERN AUSTRALIA 1853-1976

Year	Ore and concentrate tonnes	Contained copper tonnes	Year	Ore and concentrate tonnes	Contained copper tonnes
1853	a 0.5	b 0.07	1910	34 902.74	2 810.02
1854	—	—	1911	23 039.75	2 095.92
1855	2.08	b 0.21	1912	13 820.72	1 729.13
1856	57.91	b 8.68	1913	13 644.23	1 331.87
1857	81.28	b 15.61	1914	12 985.02	1 334.61
1858	440.20	b 89.68	1915	4 570.76	676.43
1859	956.61	b 131.64	1916	6 804.87	746.40
1860	525.81	b 77.62	1917	6 592.79	798.56
1861	415.56	b 65.08	1918	5 062.89	727.59
1862	796.08	b 131.31	1919	1 297.50	250.41
1863	775.25	b 131.95	1920	1 993.65	383.21
1864	1 093.27	b 174.93	1921	1 168.80	295.74
1865	900.22	b 153.00	1922	1 213.67	252.76
1866	566.45	b 101.14	1923	10 031.30	956.76
1867	342.41	b 70.84	1924	10 927.31	580.52
1868	84.33	b 17.45	1925	2 509.36	140.71
1869	157.49	b 33.45	1926-27	—	—
1870	6.10	b 1.41	1928	45.72	6.35
1871	—	—	1929	151.57	18.15
1872	—	—	1930-37	—	—
1873	57.40	b 10.07	1938	—	6.51
1874	67.57	b 12.51	1939	2.03	0.60
1875	208.04	b 38.41	1940	36.45	5.49
1876	283.48	b 56.04	1941	6.20	2.07
1877	54.36	b 11.74	1942	48.85	6.92
1878	9.14	b 2.26	1943	0.41	0.34
1879	—	—	1944	46.75	5.68
1880	8.13	b 1.94	1945	40.20	5.86
1881	—	—	1946	75.19	1.12
1882	1.52	b 0.34	1947-48	—	—
1883	5.08	b 1.21	1949	50.28	4.19
1884	119.89	b 33.43	1950	48.77	1.43
1885	121.42	b 41.87	1951	43.82	6.93
1886	253.00	b 94.63	1952	15.76	6.77
1887	23.37	b 7.62	1953	51.10	15.27
1888	88.90	b 18.54	1954	—	—
1889	138.18	b 38.89	1955	12.31	3.42
1890	8.12	b 3.24	1956	215.64	46.52
1891	266.71	c 88.03	1957	1 832.92	328.73
1892	576.10	d 193.75	1958	1 830.87	426.07
1893	50.80	c 14.15	1959	4 479.51	1 110.80
1894	—	—	1960	3 609.14	920.50
1895	839.26	d 306.04	1961	6 288.05	1 484.70
1896	6.40	c 2.17	1962	5 144.48	994.43
1897	87.38	d 21.38	1963	5 954.07	1 377.77
1898	361.11	d 83.66	1964	4 394.35	1 085.85
1899	3 011.57	550.54	1965	2 084.43	472.65
1900	6 282.38	649.88	1966	3 320.75	688.72
1901	10 120.00	1 026.68	1967	3 142.64	672.52
1902	2 298.56	150.23	1968	4 344.20	978.75
1903	20 855.75	1 021.22	1969	2 687.71	538.42
1904	4 032.60	513.13	1970	3 026.00	570.73
1905	2 427.38	327.53	1971	2 022.87	343.89
1906	7 530.62	919.71	1972	1 015.73	311.42
1907	19 283.00	2 649.84	1973	35.00	10.18
1908	8 427.42	1 242.29	1974	—	—
1909	15 327.01	1 648.87	1975	—	—
			1976	6 200.00	1 673.00
			Total	323 302.34	42 229.09

a = Estimate

b = Estimate from average annual London copper price and declared value of ore exported (Northampton Mineral Field)

c = As for (b), figures from the West Pilbara Goldfield only

d = As for (b), plus figures from the West Pilbara Goldfield copper was produced. This interval was overlapped by the first major output period of the Ravensthorpe mines, lasting from 1903 to 1918 and accounting for ore and concentrates containing 8 132 t of copper. Furthermore between 1900 to 1903 and from 1906 to 1908, 4 420 t of copper production was credited to the Anaconda and Nangeroo mines (north of Kalgoorlie)—the Anaconda mine accounted for the bulk of this figure. These three major producing areas combined to form the biggest peak in the State's copper mining history (Fig. 2).

The ensuing slump in demand, prices, and consequently in mining, was only relieved at the outset by production in 1922 to 1925 from the Narra Tarra mine, south east of Northampton, which amounted to 1 813 t of copper and formed 94 per cent of the State's total in those years. This resulted from the late discovery that the lead mineralization in the mine changed abruptly southwards into rich copper mineralization. Elsewhere in the State the bulk of the rich, near-surface secondary ores had been exhausted which, coupled with the depressed economic situation, led to a virtual cessation in copper mining from 1926 until the late 1940's. The recovery was initiated in 1944 by a new type of demand for copper ore (Table 2); it stemmed from studies by the Department of Agriculture which revealed widespread deficiencies of copper, zinc, and molybdenum in the soils of the State. Low-grade (averaging 10 per cent copper) ore derived initially from carbonate ores, was used as an additive to standard fertilizer. The name *cupreous ore* was adopted to avoid confusion with copper ore from which the metal would be extracted. Thus it became possible to exploit previously uneconomic mineralization, including the tailings from previous high-grade mining operations in some areas. Increase in production was stimulated by the rapid post-war expansion in the development of light agricultural land. A large number of old mines were re-opened but two-thirds of the total production of cupreous ore came from three mines: Thaduna (northeast of Meekatharra), Copper Hills (south-southeast of Marble Bar), and Whim Creek. Cupreous ore production reached a peak of 12 049 t in 1959, but had declined to a low level by 1965 (Fig. 2) because of substitution by imported copper sulphate, which provided an uninterrupted supply of chemically more consistent, dust-free and lower cost fertilizer copper.

TABLE 2. ANNUAL PRODUCTION OF CUPREOUS ORE AND CONCENTRATES WESTERN AUSTRALIA 1944-1976

Year	Cupreous ore and concentrates tonnes	Contained copper tonnes	Year	Cupreous ore and concentrates tonnes	Contained copper tonnes
1944	81.28	10.09	1959	12 049.13	1 121.78
1945	261.12	30.47	1960	7 850.82	761.55
1946	73.16	6.40	1961	7 502.33	740.43
1947	516.15	42.32	1962	9 424.05	469.32
1948	262.80	29.85	1963	3 286.66	463.42
1949	258.06	25.29	1964	2 231.95	401.50
1950	985.42	83.07	1965	1 096.07	163.53
1951	1 358.51	128.25	1966	977.71	137.95
1952	1 669.97	175.67	1967	788.59	102.60
1953	1 947.67	167.31	1968	700.90	91.68
1954	4 824.32	402.36	1969	1 146.59	135.87
1955	7 860.40	679.91	1970	613.68	118.00
1956	7 837.11	673.99	1971	435.00	50.98
1957	4 713.14	476.51	1972-		
1958	7 766.40	698.42	1976	—	—
			Total	88 518.99	8 388.52

TABLE 3. ANNUAL PRODUCTION OF COPPER AS A BY-PRODUCT OF NICKEL ORE TREATMENT WESTERN AUSTRALIA 1968-1976

Year	Copper, tonnes	Year	Copper, tonnes
1968	741.93	1973	372.00
1969	933.35	1974	267.00
1970	2 129.30	1975	678.00
1971	954.11	1976	1 419.97
1972	724.61		
		Total	8 220.27

TOTAL COPPER PRODUCTION FROM ALL SOURCES:58 837.88 t.

A few years before cupreous ore production reached a peak, a revival in copper mining began at Ravensthorpe. Treatment of old tailings began in April 1957 and production of underground ore followed soon afterwards. In the period from 1957 to 1971 concentrates containing nearly 12 000 t of copper were produced, the bulk of the ore came from the Elverdton mine and smaller amounts were contributed by the Beryl, Marion Martin and Mount Cattlin mines. Operations ceased in March, 1971 in the face of sharply falling copper prices and the increasing costs of mining steeply inclined, narrow and low-grade (1.5 to 2.0 per cent copper) ore bodies. During the active mining period few years were profitable to the operating company, Ravensthorpe Copper Mines N.L., which expended large sums on rehabilitating and developing the producing mines, and on surface and underground exploration (including trial mining) of other old mines in the district. The Bureau of Mineral Resources carried out airborne and ground geophysical surveys in 1960 and 1965 respectively, in an attempt to discover extensions to known ore bodies and new deposits.

The penultimate phase of copper ore mining in the State was a short-lived revival at the old Ilgarari mining centre (southwest of Newman) where ore and concentrates containing 405 t of copper were produced from 1971 to 1973.

The discovery of the Kambalda nickel deposits in 1966 ushered in the current phase of copper production which derives from copper contained in nickel ore. This source seems likely to be the only substantial and continual producer of copper in Western Australia for the foreseeable future. Production from 1968 to 1976 totals 8 220 t of copper (Table 3). Currently copper sulphide concentrates containing about 60 per cent copper are shipped to Port Kembla for treatment.

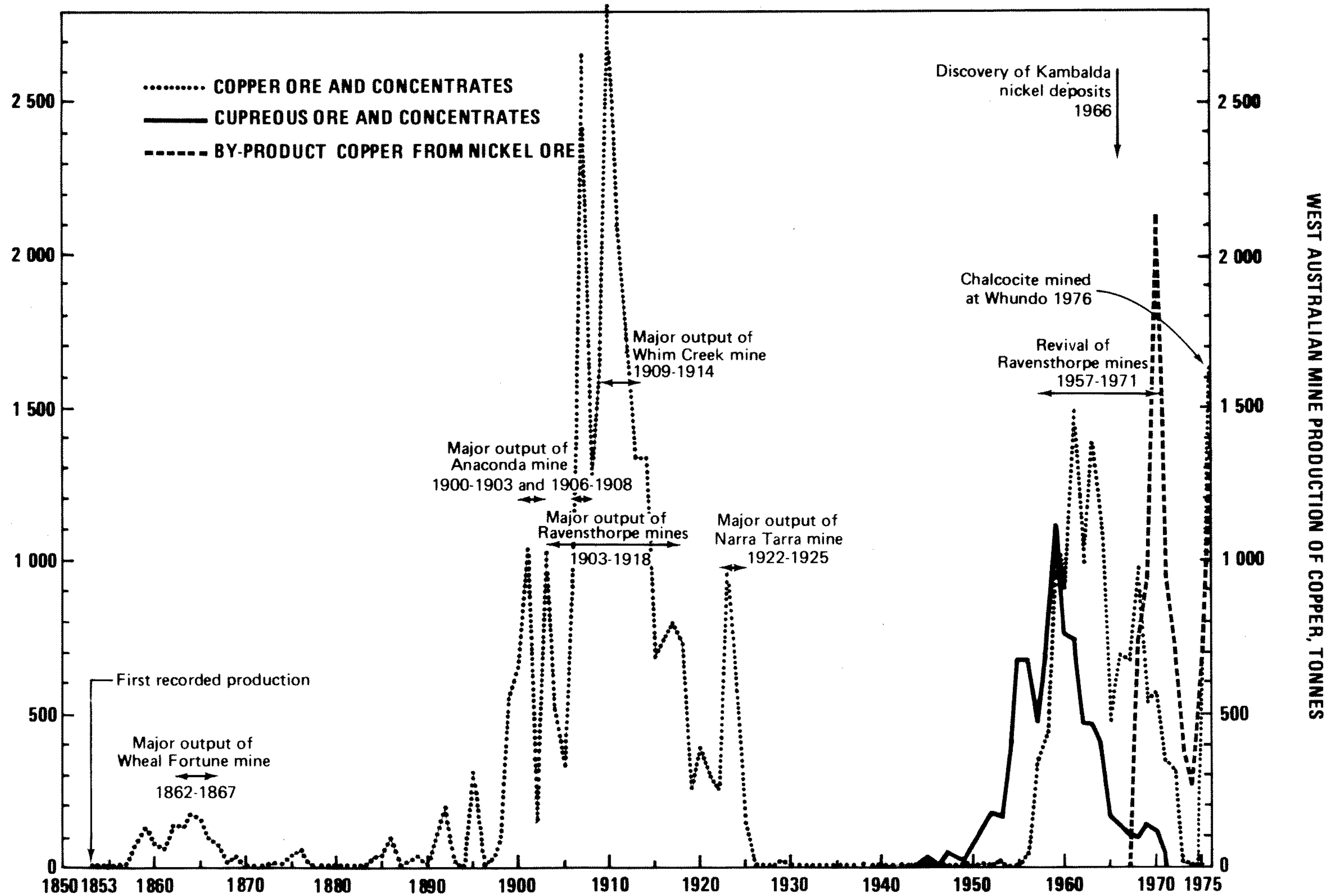

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Figure 2. Mine production of copper in Western Australia 1853-1976

From May to October 1976, approximately 6 200 t of medium-grade (27 per cent copper) chalcocite ore was extracted by open-pit mining at Whundo, an old mining centre southwest of Roebourne.

TREATMENT METHODS

Both mining and treatment methods were primitive in the Northampton lead-copper mines in the 19th century. Only the larger mines, (for example Wheal Fortune) used mechanical means such as jigs, as an alternative or additional method to the hand sorting of ore. The ores and concentrates of copper were of high enough grade (30 per cent copper) to be shipped directly to smelters in Europe or eastern Australia (where smelting was twice as costly as in Britain), and unlike lead ores, were not generally present in sufficient quantity to encourage attempts at local smelting. Woodward (1895, p. 123) records that acid mine waters pumped from the main shaft at the Wanerenooka mine were run into a ditch containing scrap iron which was gradually replaced by copper from the weak sulphate solution. This was probably the first attempt at leaching copper ores in the State, in this case using the natural oxidation of pyrite in the ore as a means of generating sulphuric acid from meteoric water. The acid attacks the copper sulphides also, and produces copper sulphate.

Few of the copper discoveries made elsewhere in the State at the end of the 19th century were of sufficient size and of remote enough location to encourage efforts at local smelting after hand-picking or crude mechanical concentration. Small smelting furnaces were operational for a few years at Mons Cupri (southeast of Whim Creek) and Gabanintha (south-southeast of Meekatharra) in the early 1900's, but were unprofitable because of the cost of obtaining fuel and flux required to deal with the siliceous ores being mined. The only sustained smelting operations were at Ravensthorpe and the Anaconda (east of Leonora) mines. In the latter area, the medium-to-high-grade carbonate and oxide ores were treated from 1899 to 1917, the carbonate ores were apparently self-fluxing. Up to three small reverberatory furnaces were used which produced a matte containing about 50 per cent copper (Simpson and Gibson, 1907, p. 29).

The first smelter in the Ravensthorpe district opened in 1903, followed by two smelters erected by the Government in 1904 and 1906 (Sofoulis, 1958b, p. 19). The main locus of smelting was a few kilometres east-southeast of the town, where private enterprise took over and enlarged the smelters in the mid-1900's, only to cease operations in early 1911. This forced the closure of many of the copper mines which were exploiting ore of too low grade (less than 10 per cent) to enable profitable return from smelting in eastern Australia. The gold mines in the area also had problems as their workings deepened and encountered gold in cupriferous iron sulphides. The copper inhibited successful cyanidation, consequently much gold was lost in the sulphidic tailings. The Government rendered assistance by leasing the old smelter in 1913 and upgrading it in mid-1914 ready for treatment, at a rate of about 100 t per day, of ores and concentrates bought on a declared tariff. A mechanical concentrating plant (McKeown, 1917, pp. 16-25) was set up adjacent to the smelter, and provided the bulk of the feed by upgrading ore containing about 4 to 6 per cent copper. Concentrates and fine ore were then sintered. Direct smelting ore contained 8 to 9 per cent copper. The raw material was first treated in a water-jacketed blast furnace with coke, limestone, and ironstone, to produce a matte (30 to 32 per cent copper) which was then converted at a rate of about 8 t per day into blister copper containing about 99 per cent copper and 125 g/t of gold. This was shipped to Port Kembla for electrolytic refining (to 99.93 per cent plus copper) and extraction of the contained gold and silver. The closure of the smelter in 1918 coincided with a fall in copper prices, and with a need for flotation methods to improve the recovery (about 65 per cent copper at best) of the concentrating mill and thereby make smelting economic.

Depletion of reserves of the richer oxide-carbonate copper ore prompted experimentation with new treatment methods at Whim Creek in the period 1911 to 1913. Previously, hand-picking and bagging in the mine, or passage through a plant of breakers, screens and shaking tables (plus hand-picking of the richer ore), were the only ore-dressing methods used. In 1911 to 1912 a 'Murex Magnetic Separator' plant was built in which low-grade secondary ore crushed to 20 to 25 mesh was added to an oily reagent containing finely ground magnetite. The mixture was agitated then flooded over shaking tables and conveyors. Both magnetite and ore particles were preferentially attracted to the oil to be drawn off by magnets at the end of the cycle (Blatchford, 1921, p. 27). Low returns and the high cost of the additives required probably led to an early termination of this plant's life. A more practical attempt to deal with the low-grade secondary ore (much of it in dumps) and to use some pyritic ore was made in 1920 with the installation of a 'Pechey Leaching Process' plant, similar to one successfully used to treat waste dumps containing 3.2 per cent copper at Mount Hope, New South Wales. At Whim Creek, the process was primed by the addition of finely ground oxide-carbonate ore (6 per cent copper) to dilute sulphuric acid in leaching vats. The resultant iron and copper sulphate solution was pumped up through a series of filter vats floored with pyritic ore, thus generating more sulphuric acid and sulphate solution. This solution was piped through fifteen precipitation vats containing scrap iron, which precipitated 'copper cement' (70 per cent copper). The residual solution, now rich in ferrous sulphate and impoverished in copper sulphate, was piped in rotation into small shallow rectangular depressions (sometimes with a layer of pyritic ore added) established on top of the secondary ore dumps. This dump leaching caused the dissolution of copper and the oxidation of ferrous to ferric sulphate; the resulting solutions were pumped into converter vats along with sulphur dioxide (from roasted sulphur) under pressure. The ferric sulphate reacted to form ferrous sulphate and sulphuric acid which was returned to the leaching vats to complete the cycle. The main drawbacks appear to have been the slowness of the process and, particularly at Whim Creek, the need for a reliable and adequate water supply (Blatchford, 1921). Proposals for Government assistance with the latter were unsuccessful. After experiments using sea water, application for assistance in building an enlarged and modified heap leaching plant prompted a further report (Wilson, 1928, pp. 67-72), but again with no result. Further attempts at leaching the low-grade oxidized ore were made in 1962-1964, by Depuch Shipping and Mining Co Ltd—Dowa Mining Ltd., who also established a short-lived milling and flotation plant for producing cupreous concentrates. In 1974-1975 the current operators, Whim Creek Consolidated N.L., concluded that either leaching in sacrificial vats or gravity concentration was the only economic means of extraction at current metal prices.

A key factor in the mining revival at Ravensthorpe in 1957 was an efficient treatment plant (Moyses, 1965, pp. 132-133) for the low-grade (1.5 to 2.0 per cent) sulphide ores. Jaw and cone crushers provided the feed for ball mills, one of which was reserved for ore from the Mount Cattlin and Beryl mines as this contained coarse gold suitable for recovery by straking and amalgamation. Feed from the other ball mill was separated in a cyclone and the overflow (fines) from this were conditioned with sodium ethyl xanthate and a frothing agent before two phases of flotation. After thickening, filtering and drying the concentrates contained 19 to 25 per cent copper, representing 89 to 95 per cent recovery, plus about 12 g/t of gold and 65 g/t of silver. The capacity of the plant was some 10 000 t of ore per week.

Most of the production from the recent mining venture at Ilgarari was of hand-sorted high-grade (30 to 35 per cent copper), direct-shipping ore. The lower grade ores were stockpiled. Treatment of these ores by a small heavy-media separation plant was tried in 1972, but it was found that the tailings were rich enough in copper to require further treatment by flotation after fine grinding. This did not eventuate.

Commonly the cupreous ores produced in the State have simply been hand picked and crushed, except for the bigger operations (Copper Hills, Thaduna and Whim Creek) based on lower grade ores where flotation plants were necessary. Sulphide ore concentrates from Copper Hills were converted to basic copper sulphate for the fertilizer trade. When the ore at Copper Hills became too low grade for economic carting to the Halley's Comet gold mine (near Marble Bar) for treatment, a simple in situ leaching plant was set up in 1970. This closed in 1972 with the drop in prices and later efforts to extend the plant and include electrolytic precipitation did not bear fruit.

CHAPTER 2

Geochemistry and Mineralogy of Copper

ABUNDANCE IN THE EARTH'S CRUST

The average abundance of copper in the crust is about 55 ppm (Taylor, 1965, p. 177) but the element is very unequally distributed between the various rock types making up the crust (Table 4). The world average figures show that in general mafic igneous rocks contain the most copper, although the regional and local averages demonstrate a wide range of values.

TABLE 4. AVERAGE ABUNDANCE OF COPPER IN SOME COMMON ROCKS AND SEDIMENTS

Rock	Number sampled	Copper (ppm)	Source
A. WORLD AVERAGES (preferred value given first)			
ultramafic		30, 10, 20	Goles, 1967; Taylor, 1965; Vinogradov, 1962
dunite		10	Vinogradov, 1962
basalt		100, 87	Taylor, 1965; Turekian and Wedepohl, 1961
amphibolite		107	Floyd, 1968
intermediate igneous		35	Vinogradov, 1962
syenite		10	Taylor, 1965
nepheline syenite		10	Gerasimovsky, 1974
granodiorite		30	Taylor, 1965
granite		10	Taylor, 1965
shale		50, 45	Taylor, 1965; Turekian and Wedepohl, 1961
black shale		70	Vine and Tourtelot, 1970
greywacke		40	Taylor, 1965
sandstone		10-20, 1-9	Pettijohn, 1963; Turekian and Wedepohl, 1961
limestone		4	Turekian and Wedepohl, 1961
B. REGIONAL AND LOCAL AVERAGES			
mid-Atlantic Ridge pillow basalt	15	85	Keays and Scott, 1976
basalt, Hawaii	76	155	Clarke, 1924
flood basalt, Columbia River U.S.A.		370	Clarke, 1924
Keweenawan basalt U.S.A.		65	Jolly, 1974
Canadian Shield basalt	205	109	Baragar and Goodwin, 1969
Abitibi Belt basalt, Canada	113	118	Descarreaux, 1973
Canadian Shield andesite	66	94	Descarreaux, 1973
Canadian Shield salic volcanic	60	44	Baragar and Goodwin, 1969
Abitibi Belt dacite and rhyodacite	64	65	Descarreaux, 1973
Abitibi Belt rhyolite	11	22	Descarreaux, 1973
Canadian Shield, "quartz-eye" porphyries	12	52	Hopwood, 1976
B. REGIONAL AND LOCAL AVERAGES—Continued			
Taupo Volcanics (rhyolite), N. Zealand		6	Taylor and others, 1968.
granitoids associated with porphyry copper deposits, Caribbean area		61	Kesler and others, 1975a, 1975b
Precambrian rhyolite, Missouri, U.S.A.	30	1.5+	Connor and Shacklette 1975
banded iron formation, Minas Gerais, Brazil	89	22	Dorr, 1973
argillaceous rock, Italy		192	Carobbi and Pieruccini, 1943
Cambrian alum shales, Sweden		185	Armands, 1972
phosphatic shale, Wyoming-Idaho, U.S.A.		100	Vine and Tourtelot, 1970
pelagic clays, Pacific Ocean		323	Cronan, 1969
manganese nodules, Pacific Ocean		3026	Cronan, 1972
manganese nodules, Australian region		3768	Noakes and Jones, 1975
silt, Mississippi River, U.S.A.		34	Clarke, 1924
Fountain Formation arkose, Colorado, U.S.A.	80	8+	Connor and Shacklette, 1975
Sauk sequence sandstone, West U.S.A.	400	5+	Connor and Shacklette, 1975
Pennsylvanian sandstone, Kentucky, U.S.A.	152	8+	Connor and Shacklette, 1975
Mississippi chert, U.S.A.	20	1+	Connor and Shacklette 1975
Sauk sequence shale, U.S.A.	336	14+	Connor and Shacklette 1975
Devonian and Mississippian black shale, U.S.A.	88	130+	Connor and Shacklette, 1975
Sauk sequence limestone and dolomite	392	2+	Connor and Shacklette, 1975
Pennsylvanian limestone and dolomite	80	12+	Connor and Shacklette 1975
Tertiary arkose, southwest California, U.S.A.	26	12	Kamp and others, 1976.

+ = geometric mean

Copper contents decrease in the igneous series from mafic to felsic and also from mafic to ultramafic, though in detail the copper content of ultramafic rocks is very variable (Table 5). Alkaline igneous rocks seem to be relatively impoverished in copper when compared with saturated rocks of similar silica content (Gerasimovsky, 1974). Data on felsic volcanic rocks throughout the world are meagre, though Archaean terrains in Canada (Table 4) and Australia (Table 5) are comparatively well represented. The figures indicate a wider spread of copper contents for these rocks versus granitoid rocks of similar major element composition, but in Phanerozoic calc-alkaline terrains the high, and in some cases ore grade (i.e. 4 000 to 8 000 ppm Cu), values of some subvolcanic porphyritic granitoids (including the so-called "porphyry coppers") are noteworthy. The mean values for sedimentary rocks are poorly defined compared with igneous rocks. Carbonate and silica-rich sedimentary rocks have understandably very low amounts of copper, with values in clastic rocks increasing with pelitic content. Shales rich in carbonaceous or graphitic material are notably anomalous, and pelagic clays on the ocean floors may prove to be enriched in copper on a global scale, though at an order of magnitude less than manganese nodules.

Examination of the regional and local averages of metamorphosed Archaean volcanic rocks from the Canadian and West Australian shields (Tables 4 and 5), reveals differences in the copper contents of similar rock types, which could indicate that certain areas of the respective shields are copper enriched or copper depleted. A comparison of bulked Canadian Shield rocks with Abitibi Belt rocks suggests that the latter region may be copper enriched; the abundance of massive copper-zinc sulphide deposits in the Abitibi Belt is well known. However, care must be exercised as copper may be mobilized, especially during the very low-grade static-style metamorphism of volcanic piles. Thus in the Keweenawan area stratabound copper deposits occur in altered zones within a basaltic pile which is characterized by below average copper content (Jolly, 1974).

TABLE 5. AVERAGE ABUNDANCE OF COPPER (IN PPM) IN SOME ARCHAEAN ROCKS FROM WESTERN AUSTRALIA

GRANITOID ROCKS		
Darling Range, Greenbushes (9)	10[1]	
Moolyella Adamellite (9)	4[1]	
foliated granitoids, E. Pilbara (12)	7[1]	
granitoids, northeastern Yilgarn Block (252)	15[2]	
Marda, central Yilgarn Bock (5)	7[3]	
granitoids and gneisses, central Yilgarn Block (82)	8[4]	(s=8.5)
SUPRACRUSTAL ROCKS		
metabasalt, Yilgarn Block (562)	107[5]	(s=75)
amphibolite, Yilgarn Block (75)	66[5]	(s=56)
metabasalt, northeastern Yilgarn Block (140)	76[6]	
metadolerite, northeastern Yilgarn Block (115)	76[6]	
andesite, Marda (15)	50[3]	
meta-dacite, Soanesville, E. Pilbara (26)	61[7]	
acid volcanic, Marda (14)	7[3]	
acid metavolcanic, E. Pilbara (8)	6[7]	
acid metavolcanic, northeastern Yilgarn Block (56)	23[6]	
metaperidotite flow, Mount Clifford (11)	38[8]	
metaperidotites, Mount Clifford area (9)	14[8]	
metaperidotite flow, Murphy Well, E. Goldfields (10)	69.5[9]	
tremolite-chlorite rocks, Kambalda (14)	56[10]	(s=41)
talc-chlorite-carbonate rocks Kambalda (33)	31[10]	(s=18)

Sources: 1. Blockley, in press 2. Davy, 1976. 3. Hallberg and others, 1976. 4. L. F. Bettenay, pers. comm., 1976. 5. J. A. Hallberg, pers. comm., 1976. 6. Davy, in press. 7. Hickman and Lipple, 1975. 8. Barnes and others, 1974. 9. Lewis and Williams, 1973. 10. Ross and Hopkins, 1975.

Notes: i. Number of samples shown in brackets.
ii. s = standard deviation.

BEHAVIOUR IN ROCK-FORMING PROCESSES

The copper present in fresh igneous rocks tends to form minute grains of sulphide minerals rather than to substitute as a trace element in oxide or silicate minerals. Experimental studies indicate that in a basic magma the partitioning of copper into a sulphide liquid is about fifty times that into a silicate liquid (MacLean and Shimazaki, 1976). Copper is therefore a chalcophile element although trace amounts of it, probably as Cu^{+} or Cu^{2+} ions, have been recorded in almost all of the common rock-forming minerals. The rules for substitution during magmatic differentiation based on similarity of ionic radius (Goldschmidt, 1937) predict that Cu^{+} (0.96Å), should substitute for Na^{+} (0.97Å) or to a lesser extend for Ca^{2+} (0.99Å) and Cu^{2+} (0.72Å) for Fe^{2+} (0.74Å). Behaviour inconsistent with these predictions is caused (i) by the strong chalcophile nature of copper and (ii) by more complex controls on the bonding of copper in oxides and silicates than those suggested by Goldschmidt's rules. Consideration of the effects of electronegativity (Ringwood, 1955), crystal field stabilization energies (Curtis, 1964) and relative bonding energies (Nockolds, 1966), all leads to the conclusion that copper should be excluded from crystal structures with preference shown for sodium and ferrous iron.

Therefore the theoretical distribution of copper in a differentiated igneous rock series is as follows:

(i) as sulphide grains in all rocks of the series;

(ii) concentrated as a trace element in oxide and silicate minerals of the later rocks; and

(iii) in sulphide minerals crystallized from residual hydrothermal solutions.

Studies of well established differentiated mafic rock series, such as the Skaergaard intrustion (Wager and Brown, 1967), the Keweenawan lavas (Cornwall and Rose, 1957) and the Tasmanian dolerites (McDougall and Lovering, 1963) confirm this pattern. It is widely accepted (Wager and Brown, 1967) that cupriferous sulphides found throughout igneous rock series have crystallized from small amounts of immiscible sulphide liquids in the silicate magma; direct observational evidence supports this (e.g. Skinner and Peck, 1969). Commonly the separation of such an immiscible liquid takes place at an early stage. A gradual increase in the copper content of silicates, particularly ferromagnesian minerals such as pyroxene, hornblende and biotite, takes place as differentiation and solidification proceed. However the appearance of a separate (perhaps more iron-rich) sulphide liquid later, may cause a sharp drop in the copper content of silicate minerals. The primary distribution of copper in any given igneous rock complex is unlikely to be simple (e.g. Putnam and Burnham, 1963) because of the numerous physico-chemical variables controlling equilibria within and between the silicate and sulphide magmas.

Sulphide minerals are commonly only a minor or accessory constituent of pegmatites, and there are very few examples where a gradation from pegmatite to sulphide-bearing veins can be established. Nevertheless there is abundant indirect evidence that copper is transported in hydrothermal solutions, at least partly of residual magmatic origin, as for example in the alteration zones of porphyry copper intrusions. There is direct evidence of the presence of copper, as a volatile copper chloride, in the gases of Kilauea volcano, Hawaii (Murata and others, 1964). Chlorides, sulphates, sulphides and oxides of copper have been recorded in small amounts from many recent fumarolic deposits (e.g. Zies, 1929).

Sedimentary environments are the locus of the other major rock-forming processes, the cycle commonly beginning with the oxidation and weathering of sulphides and silicates, which releases some copper ions into solution. The copper is transported in solution with common anions such as chloride, carbonate and sulphate but will only remain in solution in an oxidizing acid sedimentary environment. If the environment is nearly neutral ($pH>6.3$) or alkaline, the copper ions combine with carbonate, sulphate or chloride to form compounds of low solubility (e.g. malachite, brochantite and atacamite respectively) which are then precipitated in situ or transported in suspension. The latter describes the common environment today, but in Precambrian times an evolving atmosphere and hydrosphere probably imposed different conditions on the behaviour of copper and other elements (Strakhov, 1964). Copper sulphides would have been stable in any early Precambrian atmosphere lacking free oxygen, allowing them to behave as detrital minerals and form placer deposits as heavy oxide minerals do. The weakly acidic nature of sea water at that time would have largely retained any copper in solution. The postulated increasing Eh and pH of the hydrosphere throughout the Proterozoic probably resulted in copper being removed from catchment areas in suspension rather than solution, and in its deposition in littoral areas of the oceans instead of migration in solution farther afield. Strakhov (1964, p. 1475) suggests that the preponderance of stratabound base metal deposits in sedimentary rocks of upper Proterozoic age (ca. 900 m.y.) in Africa (the Copperbelt of Zambia-Zaire) are evidence of this change in behaviour of copper (cf. Jacobsen, 1975, p. 363).

CONCENTRATION AND DISPERSION IN ROCKS

The potential for the primary concentration of copper within crystallizing igneous rocks rests largely with the separation and accumulation of a sulphide melt from a basic magma. The ferrous iron content of the silicate magma is regarded as the major compositional control of sulphur solubility within it (Haughton and others, 1974). Fractional crystallization would therefore cause the sulphur fugacity and copper content of the liquid to rise until an immiscible cupriferous iron-sulphide-oxide liquid forms, this being contemporaneous with the separation of iron-rich mafic silicate cumulates (e.g. gabbro and norite) in the case of plutonic complexes. Thus under favourable conditions copper (and nickel)—bearing iron sulphides may occur in association with the mafic components of layered intrusions as basal concentrations (e.g. Sudbury complex, Canada; Insizwa complex, South Africa) or pipe-like deposits (e.g. Bushveldt complex, South Africa; Carr Boyd Rocks complex, Western Australia).

Magmatic concentrations of copper (and sulphur) would not be expected in felsic igneous rocks. Nevertheless the tonalitic-granodioritic intrusives associated with porphyry copper deposits seem to be inherently copper rich, this being reflected for example in the abnormally high copper contents of their biotites, caused by numerous sulphide inclusions (e.g. Al-Hashimi and Brownlow, 1970, p. 985). Isotopic data suggests that the copper and the associated intrusives were derived from upper mantle sources with little if any contribution from crustal sources (Hollister, 1975), hence the enhanced copper contents may be inherited from mafic-ultramafic rocks. On the other hand granitoid intrusions with spatially and genetically related hydrothermal cupriferous veins may or may not be anomalous in copper themselves (e.g. Bradshaw, 1967). Unfortunately there is little information on the nature of the partitioning of copper into the aqueous phase of acidic magmas. However fluid inclusion (Roedder, 1972) and experimental studies (Crerar and Barnes, 1976) indicate that large amounts of dissolved copper, iron and sulphur may be transported in a chloride solution. The chloride content of porphyry copper fluid inclusions may correlate directly with the copper content of the rock (e.g. Cox and others, 1975). The main controls on the precipitation of copper sulphides from such solutions, in the case of porphyry copper deposits, are probably falling temperatures and dilution of the chloride solution by mixing with meteoric water. Both effects dramatically reduce solubilities (Crerar and Barnes, 1976, p. 790).

Chloride solutions ($NaCl-H_2O$ or sea water) are also efficient at leaching base metals, including copper, from suitable source rocks such as basalts (Dickson and Ellis, 1976). This probably occurs extensively at the present sea water-basalt interface in the ocean basins, and more efficaciously in the mid-ocean ridges where high geothermal gradients may generate large hydrothermal leaching systems in the basalt pile (e.g. Corliss, 1971; Dymond and others, 1976). Such processes may be partly responsible for the high metal contents of some pelagic sediments and manganese nodules (Table 4), though some dense metalliferous brines probably result from the dissolution of evaporites (e.g. Red Sea). There is now widespread acceptance that hypogene metalliferous hydrothermal brines (or "fumarolic exhalations") expelled into a subaqueous environment played the major part in depositing stratabound base metal sulphides in ancient and modern volcano-sedimentary basins. The density and temperature of the brine (ore fluid) on entering the water mass may be critical in determining the form, size and concentration of the resulting sulphide deposit, and its spatial relationship to the issuing fissure (Sato, 1976).

Copper transported via rivers to the oceans is most likely to be highly dispersed, but may become concentrated by adsorption on clay minerals, organic matter or manganese nodules. The release of adsorbed metals from the clay fraction during diagenesis followed by circulation in magnesian brines (e.g. as cuprous chloride complexes (Rose, 1976) to littoral areas where precipitation by anhydrite and hydrocarbons (which reduce the anhydrite and generate H_2S) takes place, has been proposed by Annels (1974) as a way of generating the stratabound copper deposits of the Zambian copperbelt. These are contained in the Lower Roan sequence of arenite, calcareous arenite, siltstone and argillite, dolomite, evaporite and pyritic carbonaceous shale. This process is essentially diagenetic although the original adsorbed copper is syngenetic. It is also important to note that the pre-Lower Roan basement of granitoids and metasedimentary rocks carries widespread copper mineralization in the form of hydrothermal quartz veins and disseminations (Pienaar, 1961), which may be the ultimate source of the diagenetically concentrated syngenetic copper. Jacobsen (1975, p. 350-355) suggests from a review of the literature that evaporite sequences (brine sources) and pyritic carbonaceous shales (hydrocarbon source) are invariably associated with stratabound copper deposits in sedimentary rocks, and that the concentration process outlined by Annels may be of general application in this context.

Diagnetic processes merge with low-grade (burial) metamorphism and both may bring about major changes in the geochemistry of the rocks, including addition or extraction of base metals, via formation waters (e.g. Jolly, 1974). Higher grade regional metamorphism is commonly associated with penetrative deformation, which may modify the original form of the deposit. Nevertheless fine mineralogical layering and other primary features may be preserved in some parts of a metamorphosed ore body, whereas elsewhere in the same deposit remobilization of massive ore into low stress areas such as fold hinges and tension fractures has occurred, with enrichment in low strength minerals like chalcopyrite (e.g. Mikkola and Väisänen, 1972). Veins of massive sulphide within footwall metabasalt or disseminated ore at Lunnon Shoot, Kambalda are chalcopyrite rich (Ross and Hopkins, 1975, p. 109), a feature also indicative of the mobility of this mineral during regional metamorphism. However it is not known if regional metamorphism is generally effective in upgrading disseminated cupriferous sulphides to massive ore bodies, rather than selectively redistributing components of originally massive sulphide as described. Such upgrading at least seems possible on a small scale in the case of iron-nickel-copper sulphides as shown by Barrett and others (1976).

Supergene dispersion and concentration affects most copper deposits at or near the surface of the crust. Close to the water table (or the level of an ancient water table) a concentration of secondary sulphides, richer in copper than the primary ore, commonly develops. This is overlain by a leached zone or gossan containing the insoluble compounds remaining after weathering and oxidation of the primary sulphides. Under weakly acid conditions much copper would enter solution with sulphate and chloride ions,

TABLE 6. COMPOSITION, COPPER CONTENT, HARDNESS AND SPECIFIC GRAVITY OF SOME COPPER MINERALS

Mineral	Ideal formula	Cu weight percent (if pure)	Vickers indentation Hardness (opaques) and Moh's hardness*	Mean specific gravity
Atacamite	$Cu_2(OH)_3Cl$	59.5	3.0-3.5*	3.76
Azurite	$Cu_3(CO_3)(CO_2)\ 2(OH)_2$	55.3	3.5-4.0*	3.77
Bornite	Cu_5FeS_4	63.3	68-124, 3.0*	5.09
Brochantite	$Cu_4(SO_4)(OH)_6$	56.2	3.5-4.0*	3.97
Chalcanthite	$CuSO_45H_20$	25.4	2.5*	2.29
Chalcocite	Cu_2S	79.9	58-99, 2.5-3.0*	5.79
Chalcopyrite	$CuFeS_2$	34.6	174-219,3.5-4.0*	4.09
Chrysocolla	$CuSiO_32H_2O$	36.2	1.5-2.5*	2.40
Copper	Cu	100	48-143, 2.5-3.0*	8.94
Covellite	CuS	66.5	59-129, 1.5-2.0*	4.68
Cubanite	$CuFe_2S_3$	23.4	150-264, 3.5*	4.03
Cuprite	Cu_2O	88.8	3.5-4.0*	6.10
Digenite	Cu_9S_5	78.0	30-83, 2.5-3.0*	5.61
Enargite	Cu_3AsS_4	48.4	133-383, 3.0*	4.46
Malachite	$Cu_2(CO_3)(OH)_2$	57.5	3.5-4.0*	3.85
Pseudomalachite	$Cu_5(PO_4)_2(OH)_4H_2O$	53.5	4.5-5.0*	4.20
Tennantite	$Cu_{12}As_4S_{13}$	51.6	251-425, 3.0-4.0*	4.64
Tenorite	CuO	79.9	3.5*	6.10
Tetrahedrite	$Cu_{12}Sb_4S_{13}$	45.8	251-425, 3.0-4.0*	5.02

leaving a residue of relatively insoluble compounds such as copper carbonates (e.g. malachite), iron hydroxides (e.g. limonite), quartz and phyllosilicates. The dissolved cupric ions move downwards, react with primary sulphides, and are precipitated as minerals such as covellite and chalcocite by displacing iron, zinc and other metals because of the much lower solubility of the copper sulphides. These secondary sulphides would replace chalcopyrite and iron sulphides, but supergene sulphides also form separate crystals because of the direct attack by acid ground waters on the more soluble iron sulphides themselves. This releases sulphate and hydrogen sulphide ions which precipitate supergene copper sulphides: it is the most important process in supergene enrichment and is obviously dependent on the amount of pyrite and pyrrhotite present in the ore. Pyrrhotite is more soluble than pyrite, so pyrrhotite-rich ores may generate thicker supergene zones. Pseudomorphic replacement textures diagnostic of the primary sulphides present are therefore not commonly developed in gossans over copper deposits, especially the fine to medium-grained types which characterize most examples in the State. If the groundwater is only slightly acid or is alkaline, little copper would enter solution because basic copper sulphates and chlorides (in addition to carbonates) of low solubility precipitate, plus copper oxides or the native metal. Under such conditions only a weakly developed secondary sulphide zone would be expected. Reactive wall rocks, such as carbonates, may also inhibit supergene sulphide development, resulting instead in the precipitation of thick cappings of copper carbonates (for example Burra mine, South Australia).

MINERALOGY

A list of common copper minerals is given in Table 6. Azurite, brochantite, chalcanthite, chrysocolla, native copper, cuprite, malachite and tenorite occur in the oxidized zone of copper deposits, with atacamite being common in particularly arid, saline environments. Bornite, digenite, chalcocite and covellite occur in the supergene (secondary) sulphide zone, and chalcopyrite, cubanite, digenite and bornite are found in primary sulphide assemblages. In Western Australia the most important ore minerals are chalcopyrite, bornite, chalcocite, digenite, malachite, azurite and chrysocolla, with the three latter minerals being ubiquitous in the oxidized zone of deposits. It is probable that much digenite has been misidentified as chalcocite. In the older literature the following terms may be encountered:

(i) copper pyrites, yellow sulphide of copper—chalcopyrite;

(ii) peacock ore, variegated copper ore, erubescite—bornite;

(iii) copper glance, vitreous copper ore, redruthite—chalcocite;

(iv) ruby copper—cuprite;

(v) tile ore—earthy cuprite and limonite mixture; and

(vi) liver ore—cuprite, limonite, siderite and chalcocite mixture.

Simpson (1948, 1951, 1952) documents occurrences of rarer cupriferous minerals: tellurides, antimonides, arsenides and arsenates reported from the Golden Mile gold ores at Kalgoorlie account for many of these occurrences. Rare sulphate, phosphate and vanadate copper minerals have been recorded from scattered localities in the State.

The principal non-cupriferous sulphides in primary ores are pyrrhotite and pyrite, whereas in secondary sulphide ores supergene pyrite and marcasite may occur also. Therefore many natural sulphide ores can be represented by the Cu-Fe-S system which has been extensively investigated experimentally (summary in Craig and Scott, 1974, pp. 64-76) but is only well understood at high temperatures. Three extensive solid solution series exist at 600°C: (a) chalcocite-digenite-bornite, (b) intermediate solid solution (*iss*) and (c) pyrrhotite. Chalcopyrite is only stable below 557°C; above that temperature it decomposes to *iss* and pyrite. The compositional fields of the solid solution series may become smaller at lower temperatures. Common assemblages such as chalcopyrite-pyrite-monoclinic pyrrhotite appear to be stable at low temperatures (Sugaki and others, 1975, p 818), although the chalcopyrite-like phases talnakhite, mooihoekite and haycockite may be more abundant but have been misidentified as chalcopyrite in the past (Craig and Scott, 1974, p. 69). Cubanite breaks down to *iss* above 200-210°C. Evidently textural compositional readjustments may have occurred in common iron-copper sulphide ores which have been metamorphosed to high grades. Copper-iron sulphide minerals equilibrate very rapidly on cooling to phases stable at low temperatures. This behaviour contrasts markedly with that of silicate and oxide minerals.

A variety of minerals make up the gangue to the sulphides in copper ores, dependent on the mineralogy of the host rocks, although in hydrothermal veins quartz is very common, plus calcite, dolomite, or barite in some places. Magnetite is present in many stratabound ores in crystalline Precambrian regions.

CHAPTER 3

Geological Setting and Diversity of Copper Mineralization in Western Australia

THE GEOLOGICAL SETTING: TECTONIC PROVINCES

Four types of tectonic provinces can be broadly distinguished, as follows:

(a) Archaean granitoid-gneiss-supacrustal ('greenstone') terrains, typified by a wide range of metamorphic grade and tectonic style;

(b) Proterozoic metamorphic belts characterized by polyphase metamorphism, deformation and igneous activity;

(c) Proterozoic sedimentary basins which are unmetamorphosed or only mildly metamorphosed, but are folded except marginal to rigid Archean terrains; and

(d) Phanerozoic sedimentary basins that are unmetamorphosed and are undeformed or only gently folded.

These types of provinces are distinguished and named on Plate 1, which also shows the distribution of copper deposits in the State.

The tectonic provinces and their currently known age spans are listed in Table 7 in approximate order of antiquity. The older ages for the Proterozoic metamorphic belts should be regarded as minima because several belts appear to include reworked Archaean rocks.

The abundance of copper mineralization and its importance in terms of past mine production and currently available resource and reserve figures, shows strongest correlation with the type (a) or Archaean provinces (Table 8).

The Proterozoic metamorphic belts and sedimentary basins take second and third places respectively, with the Phanerozoic basins, being almost devoid of recorded copper mineralization, occupying last place.

Description of the geological elements of each tectonic province will not be attempted. For a general account of all the provinces "The Geology of Western Australia" (Geological Survey of Western Australia, 1975) should be consulted. More recent data on the eastern part of the Pilbara Block is contained in Hickman (1975a), Lipple (1975), and Oversby (1976), and a summary of both the Pilbara and Yilgarn Blocks is given by Gee (1975). General accounts of substantial areas of the Yilgarn Block are given by Gemuts and Theron (1975), Binns, Gunthorpe and Groves (1976a), Archibald and others (1978) and Andersen and others (1976). Brakel and Muhling (1976) and Williams and others (1976) describe parts of the Bangemall Basin and the Paterson Province. The regional geology and geochronology of part of the Albany-Fraser Province

TABLE 7. SUMMARY OF TECTONIC PROVINCE USED IN THE BULLETIN

Province type (see text)	Name	Age[1] (m.y.)
(a) Archaean terrain	Pilbara Block	[2]3 500-2 900
	Yilgarn Block	3 500-2 600
(b) Proterozoic metamorphic belt	Gascoyne Province	2 200-1 600
	Halls Creek Province	2 000-1 800
	Various inliers, eastern W.A.[3]	2 000-1 100
	Albany-Fraser Province	[2]1 900-1 300
	Paterson Province (Rudall Metamorphics)	lower Proterozoic
	Northampton Block and Mullingarra Inlier (?)	1 100-1 000
(c) Proterozoic sedimentary basin	Hamersley Basin	2 400-1 850
	Kimberley Basin	1 850-1 650
	Nabberu Basin	lower Proterozoic
	Paterson Province (sedimentary rocks)	lower-mid Proterozoic
	Central and Northern Australian Platform Cover[4]	mid-upper Proterozoic
	Bangemall Basin	1 200-900
	Bentley Supergroup	1 100-1 000
	Platform cover marginal to West and South Yilgarn Block[5]	mid-upper Proterozoic
(d) Phanerozoic sedimentary basin	Bonaparte Gulf Basin	Phanerozoic
	Ord Basin	Palaeozoic
	Canning Basin	Phanerozoic
	Officer Basin	Phanerozoic
	Carnarvon Basin	Phanerozoic
	Perth Basin	post-Ordovician
	Eucla Basin	post-Jurassic

1. Largely based on whole rock Rb-Sr radiometric data on metamorphic and igneous events for metamorphic terrains, and depositional ages for sedimentary basins.
2. Excluding post-tectonic granitoid intrusions.
3. Includes Granites-Tanami Block, Arunta Block, Petermann Ranges Nappe and Musgrave Block.
4. Includes Victoria River, Birrindudu and Amadeus Basins (latter includes some Palaeozoic rocks).
5. Includes Badgeradda Group and Nilling Beds, Wenmillia Formation, Billeranga Group and Dudawa Beds, Yandanooka Group, Moora Group, Cardup Group, "Stirling-Barren Series", and Woodline Beds.

are documented by Bunting and others (1976), and preliminary radiometric data from part of the Gascoyne Province are given by De Laeter (1976). The Nabberu Basin is described by Bunting and others (1977).

DIVERSITY OF MINERALIZATION

It is evident from the geochemistry of copper that the element may partition into many geological environments, and account for a variety of types of mineralization. Furthermore, as much of the mineralization in the State occurs in metamorphic rocks, additional dispersion or concentration may have taken place. Deduction of the origins of much copper mineralization is made that much more difficult, hence an emphasis is given below to factual data and though genetic interpretations are offered in most cases these must be regarded as speculative.

The following six (plus a sundry category) broad types of mineralization form the basis for the classification scheme adopted in this bulletin. The criteria considered to be most important in this scheme are:

(i) the nature of the host rock, and of the sequence (or intrusive complex) of which it is a part; and

(ii) the geometry and contact relationships of the mineralization (e.g. stratabound versus a discordant fault filling).

Subdivision of these mineralization types is based upon more precise definition of the host rock or sequence (e.g. felsic volcanic versus volcanic-sedimentary), regional metamorphic grade, or the constitution of the mineralization (e.g. copper versus copper-zinc-lead).

Where geological features diagnostic of the environment of mineralization are obscured by deformation or metamorphism (or both), the geochemistry of pyrite and sphalerite, contained in and associated with the deposits, may be of assistance in determining ore genesis (See Appendix 1).

STRATABOUND COPPER-ZINC MINERALIZATION IN VOLCANO-SEDIMENTARY SEQUENCES (TYPE A)

Deposits of this type of mineralization are common in Archaean terrains and absent or rare in Proterozoic metamorphic belts, with the exception of the Halls Creek Province (Fig. 3). Important examples in the Pilbara Block are found at Whim Creek, Mons Cupri, Big Stubby, and Whundo-Yannery. In the Yilgarn Block the deposits at Anaconda-Nangeroo, Golden Grove, Teutonic Bore, Freddie Well and Mount Mulcahy are important. Examples from the Halls Creek Province include prospects at Koongie Park SouthWest, Mount Angelo (North), Ilmars-Little Mount Isa, Turtle Creek and Chianti.

Important features, largely of primary origin, which most deposits share are listed below in summary form.

1. *Host Rocks.* These may be felsic or mafic volcanic, volcanoclastic or sedimentary (carbonaceous especially). Felsic volcanic rocks are the commonest host, and may or may not

TABLE 8. MINE PRODUCTION OF COPPER ARRANGED BY TECTONIC PROVINCES

Tectonic PROVINCE	Copper ore and concentrates (t)	Cupreous ore and concentrates (t)	Average grade (%)	Contained copper (t)	Copper (percent of total)
Albany-Fraser Province	2.06		13.58	0.28	—
Arrino-Yandanooka District	774.30	32.51	14.84	30.70	—
Bangemall Basin	2 502.34	3 579.85	23.07	1 402.98	2.7
Bentley Supergroup (Musgrave Block)	154.71	533.80	20.76	142.94	0.3
Gascoyne Province	180.72	260.84	21.33	94.20	0.2
Halls Creek Province	13.40	8.99	19.61	4.39	—
Hamersley Basin	270.38	486.84	21.76	164.79	0.3
Kimberley Basin	94.35		24.56	23.17	—
Nabberu Basin	431.54	33 968.06	8.37	2 877.86	5.5
Northampton Block	33 329.73	35.11	12.79	4 268.21	8.2
Pilbara Block	92 118.51	32 716.28	13.68	17 078.75	32.7
Yilgarn Block	247 367.86	17 268.56	9.83	26 198.17	50.1
Totals	[2]377 239.85	88 890.84	[1]11.22	52 286.44	100.0

1. Overall average for copper and cupreous ores and concentrates combined.
2. Discrepancies with Tables 1 and 2 largely arise from the method of treatment of statistics from the Ravensthorpe-West River area. In particular large tonnages of ore (primarily mined for gold) containing small amounts of copper from the Kundip group are excluded from Table 1.

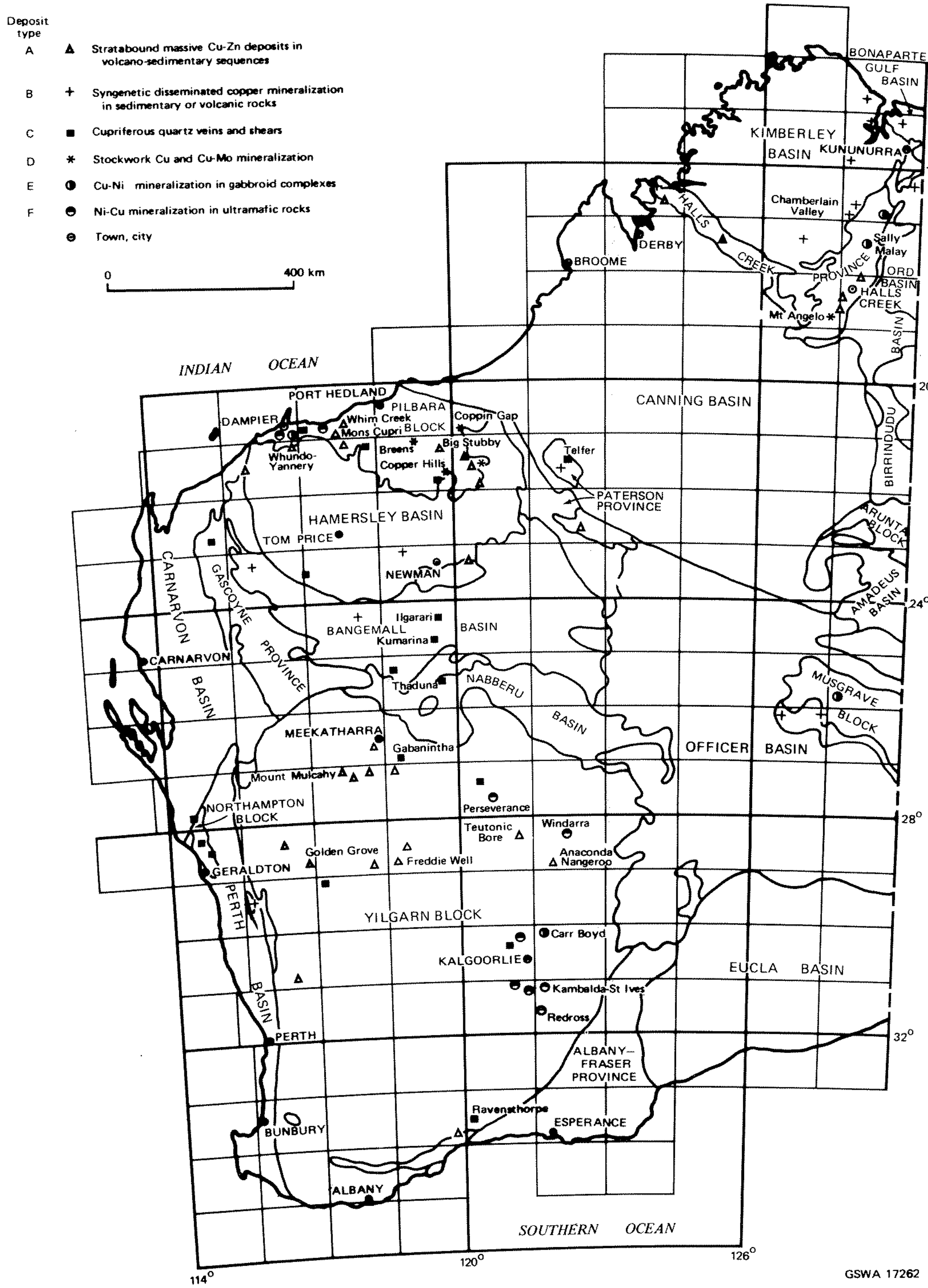

Figure 3. Distribution of major types of copper mineralization in Western Australia

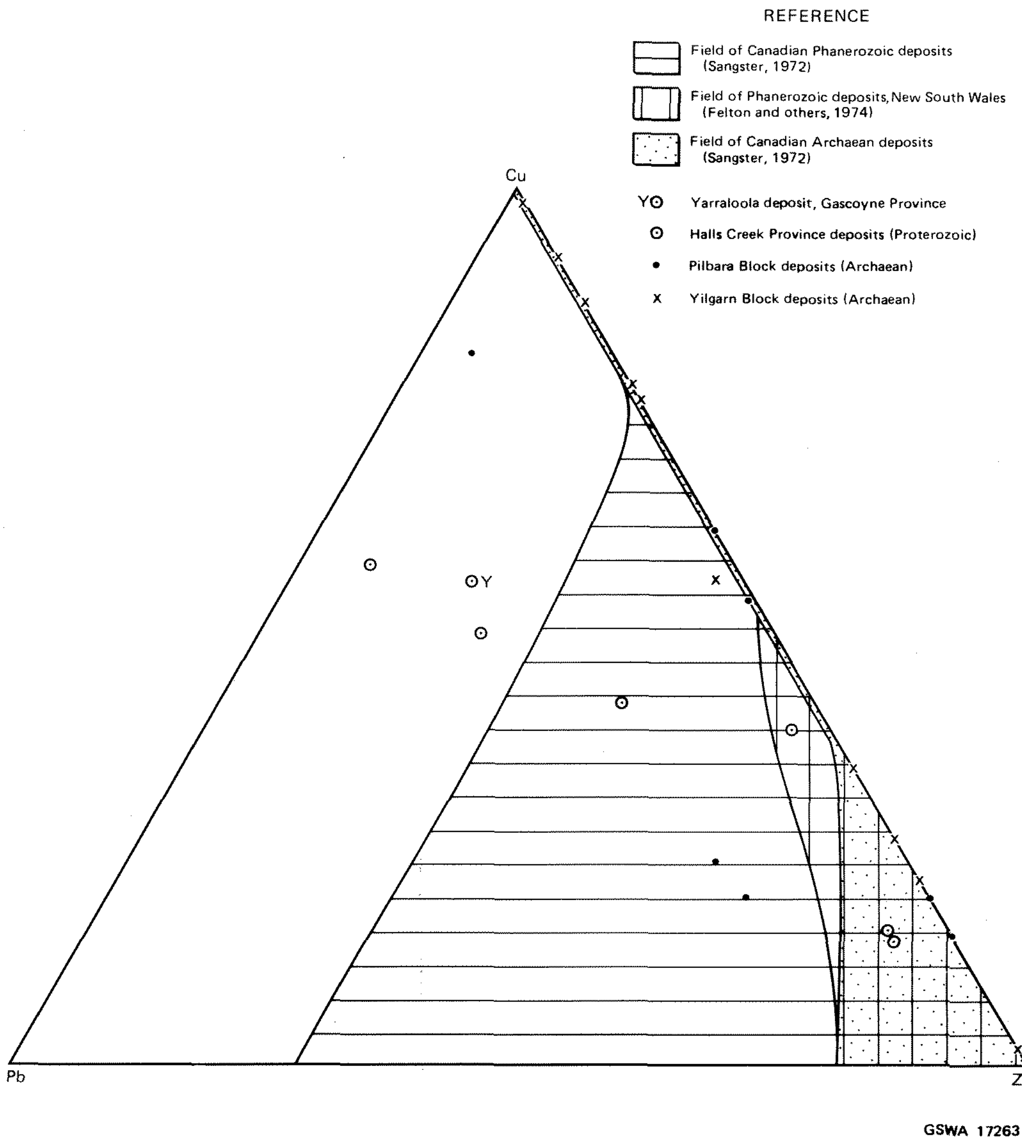

Figure 4. Copper-lead-zinc atomic proportions for stratabound volcanogenic massive sulphide deposits (Type A)

be part of a calc-alkaline sequence (the bulk are not). Lithological heterogeneity (i.e. mixed rock types, rapid facies changes) is characteristic. Disseminated iron sulphides, an abundance of chlorite, and geochemically anomalous base metal contents typify many host rocks.

2. *Stratigraphic position.* In regional terms few patterns emerge, partly because the stratigraphy itself is poorly defined. In Archaean terrains deposits occur at low (e.g. Golden Grove, Whundo-Yannery) and high stratigraphic levels (e.g. Mons Cupri, Whim Creek). Most deposits in the Halls Creek Province are in the upper part of the sequence. In local terms the host rock unit is commonly near the top of a volcanic cycle, and the mineralization is intimately associated with or capped by chert, banded iron formation or carbonaceous slate.
3. *Form of Mineralization.* The mineralization occurs as small, irregular shoots of disseminated to massive sulphides and oxides. These shoots are contained in a stratabound, conformable zone of greater lateral and vertical extent (i.e. the host rock unit) than the mineralization. Rarely, stringer to disseminated mineralization occurs in the footwall zone (e.g. Mons Cupri, Whundo). In the more deformed and metamorphosed sequences the massive shoots tend to occur in fold hinges, and are elongated parallel to the predominant fold axes or mineral elongation direction.
4. *Constitution of Mineralization.* Pyrite (commonly cobalt rich) and pyrrhotite are the dominant sulphides, accompanied by chalcopyrite, iron-bearing sphalerite, minor galena, arsenopyrite, cubanite and trace amounts of silver, arsenic, bismuth, cobalt and antimony bearing sulphides and sulphosalts. Copper: zinc ratios, where known, are commonly in the range 0.2-6.0, but there is a full range if the very zinc rich (e.g. Freddie Well, Big Stubby) and copper rich examples (e.g. Golden Grove) are included (Plate 4). The mean copper:zinc ratios for the Yilgarn Block, Pilbara Block and Halls Creek Province are 2.74, 1.87 and 0.36 respectively. Magnetite is the most important oxide mineral and may be the dominant iron mineral in some deposits (e.g. Golden Grove). Other gangue minerals are quartz, feldspar, micas, chlorite, talc, barite, calcite, magnesite, siderite and amphibole.
5. *Internal Structure.* In the less reconstituted examples fine-scale mineralogical layering and colloform textures remain (e.g. Whim Creek, Anaconda), but most textures are the result of metamorphic recrystallization. Deformation of shoots containing mixed high strength (pyrite, magnetite) and low strength minerals (pyrrhotite, chalcopyrite, sphalerite, galena) has resulted in the differential mobilization of the latter (e.g. into veins). Most ore shoots contain an imposed foliation and some are lineated or brecciated (e.g. Freddie Well).
6. *Metal Zonation.* Despite reconstitution by deformation and metamorphism, the stratigraphic top of many ore shoots or mineralized zones is zinc rich, and contains most of any lead present. The zinc rich mineralization, though discontinuous, may be more laterally extensive than the copper-rich mineralization (e.g. Golden Grove, Whim Creek). It may also be contained in fine-grained or cherty rocks of probable exhalative origin, which overlie the coarse volcanic rocks including the copper mineralization (e.g. Golden Grove, Mons Cupri).
7. *Wall Rock Alteration.* This is difficult to assess in many cases, particularly in the case of chlorite-rich host rocks, which are commonly much more extensive than the mineralization (e.g. Whundo-Yannery, Jimblebar, Whim Creek). Detailed studies indicate that the loss of potassium, sodium and calcium and the addition of iron, magnesium and aluminium may be typical (e.g. Mons Cupri, Golden Grove). Mineralogically this is expressed by the development of iron-rich chlorite, almandine or aluminosilicates (e.g. andalusite). It is feasible that some of the iron-rich minerals are a product of sulphide-silicate reactions during regional metamorphism. Silicification and spotty alteration is a feature of some host rocks (e.g. Nangeroo, Golden Grove).

In general terms many of the features described are similar to those described by Sangster (1972) as typical of volcanogenic massive sulphide deposits in the Archaean terrain of Canada (Fig. 4). Despite the effects of deformation it is clear that most Western Australian examples lack a chloritic alteration pipe and stringer mineralization in the footwall. This indicates that metal deposition was distal with respect to the issuing site of the ore fluids onto the sea floor, and that the actual site of deposition could have been controlled by the accumulation of high density metalliferous brine into sea floor (i.e. footwall) depressions (cf. Sato, 1976).

SYNGENETIC DISSEMINATED COPPER MINERALIZATION IN SEDIMENTARY OR VOLCANIC ROCKS (TYPE B)

Mineralization of this type is largely confined to Proterozoic sedimentary basins (Fig. 3), but all known occurrences are uneconomic even where grades have been enhanced by supergene processes, or by concentration into structural sites. Occurrences in Phanerozoic basins are restricted to the Palaeozoic parts of the Bonaparte Gulf and Ord Basins. Large areas of the Bangemall, Hamersley and Nabberu Basins appear to be virtually devoid of syngenetic copper mineralization, although thorough prospecting remains to be done before this is known to be the case.

Regional mapping and geochemical surveys have demonstrated the presence of widespread, but very low grade and sporadic stratiform occurrences in Lower Proterozoic rocks of the Kimberley Basin, particularly in the eastern part of the Basin, marginal to the Halls Creek Province. The cupriferous sedimentary formations are the shallow water marine parts of the (i) Elgee Siltstone, (ii) the Pentecost Sandstone and (iii) the Warton Sandstone (Plate 2). The copper is restricted to specific stratigraphic horizons in these formations which are respectively composed of (i) calcareous sandstone, chloritic shale and siltstone, (ii) chloritic, shale, siltstone and glauconitic sandstone and (iii) siltstone and ferruginous chert. Copper sulphides are only known from the Elgee Siltstone and the best grades are only in the range 0.1 to 0.4 per cent over a few metres thickness and very short strike lengths. Sedimentary structures in this formation in the Chamberlain Valley (East Kimberley region) indicate that the palaeo-shoreline was to the northeast. Disseminated malachite shows are numerous in the Middle Pentecost Sandstone but many appear to be the result of surface enrichment of very low-grade syngenetic copper present at depth. Supergene enrichment is also prominent where the Warton Sandstone is known to be cupriferous in the Yampi Peninsula area.

Disseminated copper sulphides are widespread in the lower amygdaloidal basalt flows of the Carson Volcanics, and to a lesser extent in the Hart Dolerite, both within the Lower Proterozoic section of the Kimberley Basin (Plate 2). Copper mineralization of marginal economic interest seems to be restricted to small areas of faulted or altered rock. It is possible that the Carson Volcanics are partly the source of the syngenetic copper of the Elgee Siltstone. The Carson Volcanics may also be slightly more cupriferous along the eastern margin of the Basin. Copper mineralization is also widespread in the eastern arm of the Halls Creek Province, so this is also a suitable source area for sedimentary copper. Widespread zones of alteration in the Carson Volcanics or Hart Dolerite, which might be analogous to those associated with copper mineralization in Proterozoic basalts in northern Michigan, USA, have not been identified as yet.

The Halls Creek Province and the cupriferous formations of the Kimberley Basin were probable source areas for middle and upper Proterozoic sedimentary rocks of the Birrindudu and Victoria River Basins to the east and south. Copper has been recorded from the Bungle Bungle Dolomite (Birrindudu Basin) in the Osmond Range area.

The Lower Cambrian Antrim Plateau Volcanics in the basal part of the Bonaparte Gulf and Ord Basins contain disseminated copper especially in amygdaloidal and agglomeratic horizons. Local concentrations occur in flow tops and in fractured areas, but none has yet proved to be of even marginal economic importance. Some of this copper has probably been redeposited by circulating ground water in overlying formations such as the Headleys Limestone and Blatchford Formation. Minor occurrences of secondary copper minerals are known from Devonian arenite-carbonate (probably Cockatoo Formation) in the Bonaparte Gulf Basin. It is not clear to what extent these are redeposited syngenetic versus epigenetic in origin. An association with lead-zinc mineralization of the Mississippi Valley-type suggests that the movement of metalliferous, saline formation waters from deeper parts of the basin could have been involved in ore genesis.

Remaining syngenetic copper occurrences in sedimentary rocks have been noticed (and in some cases worked) mainly because of supergene enrichment and/or concentration into structural sites. Pyritic carbonaceous shales in the southern Hamersley Basin (Roy Hill Shale Member of the Jeerinah Formation), and the western Bangemall Basin (e.g. basal Discovery Chert; Glen Ross Shale Member) are good examples. Copper contents in unweathered rock are commonly in the range 100 to 400 ppm only. Arenaceous rocks near the base of an upper Proterozoic sedimentary-volcanic sequence in the Arrino-Yandanooka area (Perenjori Sheet) carry minor amounts of disseminated secondary copper minerals, possibly derived by ground water redistribution of contained syngenetic copper.

Syngenetic copper mineralization remaining to be mentioned in volcanic rocks includes rare minor occurrences in (i) mafic volcanics of the Halls Creek Group, Bentley Supergroup (Milesia Formation), Hamersley Basin, Yilgarn Block, Pilbara Block and upper Proterozoic cover rocks west of the Yilgarn Block, and (ii) minor iron-zinc-lead-copper+fluorite disseminations in felsic volcanic rocks of cauldron subsidence volcanic associations in the Blackstone region.

CUPRIFEROUS QUARTZ VEINS AND SHEARS (TYPE C)

This type of mineralization is very common in the supracrustal rocks of Archaean terrains, and the rocks of some Proterozoic metamorphic belts and sedimentary basins. With the possible exception of the Northampton deposits, the primary sulphides are low grade (less than 2 per cent copper) and exploitation of the normally steeply inclined mineralization has been contingent on the following factors.

1. *Supergene enrichment.* Deep weathering when the water table was much deeper than now was responsible for making low-grade primary sulphides economic to work at Kumarina (oxidized to 50 m depth), Ilgarari

(130 m) and Thaduna (up to 200 m), with oxidized-supergene ore grading from 3 to 25 per cent copper, and commonly being in the range 5 to 10 per cent copper. Such enrichment of copper tenor was not prevalent at Ravensthorpe, but gold values were considerably enhanced in the oxidized zone and many copper producing mines were only economic because of their gold contents. The quartz-pyrite-chalcopyrite-gold reefs at Telfer are likewise enriched in gold in the oxidized zone (to 150 m depth).

2. *Presence of other economic metals.* Gold has been mentioned, and many gold mines in Archaean mafic to ultramafic meta-igneous rocks carried minor amounts of copper (Appendix 2), and vice versa. Silver was an important contributor to the income of some of the Ravensthorpe mines. Copper may be accompanied by gold, silver, lead, zinc, antimony, bismuth and uranium in quartz vein mineralization in the Gascoyne Province and the southwestern Hamersley Basin (Ashburton Formation). Lead and silver were the most important metals in the Northampton field, copper was ancillary and at the Narra Tarra mine (the largest single copper mine in the field) the copper-bearing part of the ore body was only found accidentally during underground development of the lead-bearing part.

The majority of occurrences are in mafic to ultramafic rocks in metamorphic terrains, and as such probably reflect leaching of syngenetic copper from these rocks by hydrothermal fluids. This was probably partly in response to thermo-chemical gradients set up during regional metamorphism. These fluids were commonly siliceous and were generally precipitated in structurally prepared sites during or after the main period of deformation. The copper-gold-silver mineralization at Ravensthorpe is exceptional in its abundance, a spatial restriction to narrow acid to basic metavolcanic units (i.e. stratabound in gross terms), and in the association with layer-parallel copper-zinc mineralization of probable volcanogenic origin (West River). These features in addition to mineragraphic and geochemical data (Appendix 1), suggest that much of the mineralization is a relocated version of originally stratabound volcanogenic mineralization of type A.

The only major deposits known in Proterozoic sedimentary basins are at Thaduna, Ilgarari, Kumarina and Horseshoe, localities which occur in a north-south oriented corridor between Meekatharra and Newman. The source of the copper is not evident, although felsic volcanic elements are present in the host rocks at Thaduna and Horseshoe. The Ilgarari and Kumarina deposits occur in east-northeast trending faults which are subparallel to a major lineament nearby that partly corresponds with an important facies change in the Bangemall Basin.

STOCKWORK COPPER AND COPPER-MOLYBDENUM MINERALIZATION (TYPE D)

Stockwork cupriferous deposits are known only from the eastern Pilbara Block (McPhee Dome, Coppin Gap, Breens, Copper Hills) and the eastern Halls Creek Province (Mount Angelo South). The host rocks are metamorphosed felsic porphyritic hypabyssal intrustions, commonly with rounded quartz and subhedral feldspar phenocrysts, and enveloping mafic to felsic volcanic rocks.

The three occurrences on the north flank of the McPhee Dome are associated with high level, perhaps subvolcanic, intrustions. Very small intense stockworks, or less dense and more extensive ones of very thin quartz-pyrite-chalcopyrite-molybdenite veins and veinlets, are mainly restricted to the enveloping country rocks. Marginal chloritization, kaolinization, sericitization, or silicification may affect the wall rocks but much of the kaolinization and sericitization is more likely a product of meteoric alteration. Overall the sulphide content is probably no more than a few per cent, and average copper plus molybdenum grades would probably be less than 0.5 per cent.

The Breens and Coppin Gap prospects also occur on the flanks of major domal structures cored by intrusive granitoid plutons which in both cases are of a late tectonic type. Several styles of mineralization are present. Strongly silicified fault or shear zones associated with stockworks of quartz and quartz-feldspar porphyry dykes, veins and veinlets are the most prominent. Pyrite and subordinate chalcopyrite and molybdenite occur in the stockwork at Coppin Gap and average about 0.3-0.4 per cent copper plus molybdenum. At Breens the stockwork is apparently only feebly mineralized but later brecciated silicified fault zones contain small lenses of massive iron-copper sulphides. Pervasive kaolinization of the host rocks may not necessarily be of hydrothermal origin; the meteoric alteration of rocks containing disseminated sulphides could produce a similar end result. Carbonation, chloritization and silicification are probably of hydrothermal origin.

The mineralization at Mount Angelo and Copper Hills lacks molybdenum and the stockwork of fractures is apparently largely filled with secondary iron-copper minerals with little or no quartz. This suggests that disseminated primary iron-copper sulphides (probably averaging less than 1 per cent copper) have been leached and deposited by ground water into the fracture system. Kaolinization and sericitization is pervasive at Copper Hills. There is little or no alteration present which can definitely be assigned to hydrothermal fluids. However deep subsurface data is needed for a proper characterization of the nature of the mineralization. Supergene enrichment at Copper Hills enabled a substantial tonnage of oxidized mineralization to be mined.

In summary, the copper-molybdenum deposits evidently have some features in common with porphyry copper type deposits of younger terrains. However important features lacking seem to be zoned hydrothermal alteration (which might relate to water-deficient felsic magmas in the early Precambrian), a varied gangue mineralogy in the stockwork veins, and an island arc type of geotectonic setting.

COPPER-NICKEL MINERALIZATION IN GABBROID COMPLEXES (TYPE E)

Mineralization of this type is rare, examples being recorded from the Yilgarn Block (Carr Boyd Rocks), the Pilbara Block (Mount Sholl), the Halls Creek Province (Bow River, Corkwood, Limestone Spring and Sally Malay) and the Musgrave Block (Giles Complex). Though metamorphosed, the gabbroid complexes are commonly little deformed and most appear to have been emplaced late in the tectonic evolution of the surrounding country rocks. Olivine gabbro, gabbro and norite make up the bulk of each complex with subordinate troctolite, pyroxenite and peridotite. Igneous layering occurs in the larger complexes (e.g. Bow River, Carr Boyd Rocks, Giles Complex).

Pyrrhotite (commonly dominant), pyrite, pentlandite, chalcopyrite and spinels (magnetite, ilmenite) are present as (i) disseminations, (clearly interstitial to relict primary igneous minerals in some examples); (ii) rare massive bands parallel to the layering; (iii) discordant veins; and (iv) discordant massive lenses or pipes including fragments of host and/or country rock (i.e. "breccia ore"). In general, types (i) and (ii) are probably largely primary and of magmatic origin, and types (iii) and (iv) are secondary, being generated by mobilization of primary sulphides into tectonic sites. Overall nickel:copper ratios are in the range 0.75 to 3.0 but are variable within each deposit, partly because of a mixture of mineralization types. The discordant veins and massive lenses or pipes tend to have lower nickel:copper ratios because of the differential mobility of the low strength mineral chalcopyrite. Indeed the presence of such copper-rich mineralization in massive form is usually the determining factor in a deposit being of economic interest (e.g. Carr Boyd Rocks and Sally Malay).

NICKEL-COPPER MINERALIZATION IN ULTRAMAFIC ROCKS (TYPE F)

Copper is very subordinate in this type of mineralization. Iron-nickel-copper sulphides occur in deposits having nickel:copper ratios falling into two distinct groups coinciding with two kinds of host rock. The host rocks are (i) thick komatiitic peridotite flows or sills near the base of thick volcanic piles (nickel:copper = 10-15:1) and (ii) dunitic dykes or sills (nickel:copper>25:1). This relationship was pointed out by Binns, Groves and Gunthorpe (1976b). The deposits currently being mined in the eastern Yilgarn Block are all of type (i), and since 1968 more than 8 000 t of copper metal has been smelted from chalcopyrite concentrates derived as a by-product of nickel mining (Table 3). The available evidence indicates that pre-existing sulphides of magmatic origin have been recrystallized and locally reconstituted during regional metamorphism (Barrett and others, 1977).

OTHER MINERALIZATION (TYPE G)

Minor amounts of copper minerals occur in association with lead-zinc minerals in Devonian carbonates at isolated localities in the Bonaparte Gulf Basin (Redbank) and the Canning Basin (Narlarla). The deposits are of the general Mississippi Valley type.

In the Balfour Downs area of the Hamersley Basin small deposits of probable supergene origin occur in joints and solution cavities in the Carawine Dolomite.

RESOURCE POTENTIAL

Known copper resources in the State are summarized in Table 9. Important resources which could become ore reserves in the near future are largely restricted to stratabound copper-zinc deposits in volcano-sedimentary sequences. These are the deposits at Golden Grove, Teutonic Bore, Whim Creek, Whundo, and near Halls Creek. Even in these examples, particularly those requiring substantial capital expenditure (e.g. Golden Grove), development will be contingent upon considerable higher copper prices than those prevailing at the time of writing. The open cut mining and sale of small tonnages of high-grade copper ore (supergene oxide-sulphide) is economically feasible in locations not too remote or too far from the coast, as illustrated by the operation at Whundo undertaken by Whim Creek Consolidated in 1976.

The prospects of finding further stratabound copper-zinc deposits in the Yilgarn Block appear bright, especially in the light of the Teutonic Bore discovery. If this prospect can be used as an indication, gossan searches will need to pay particular attention to less well exposed portions of felsic fragmental volcanic complexes with low topographic relief. These complexes are best developed in the Eastern Goldfields Province of the Yilgarn Block in : (i) the area east of the Kalgoorlie on the Kurnalpi Sheet—where so far largely barren iron sulphides only have been found; and (ii) in the Northeastern Goldfields region around Kookynie, Leonora, Duketon and Melrose. An effort should be made to define eruptive centres (e.g. Fox, 1977) and special interest may attach to coincident magnetic anomalies. There appear to be no major expanses of felsic volcanic rocks in the Murchison Province of the Yilgarn Block, nevertheless at present prospects and indications of copper-zinc mineralization per unit area of felsic rock are more numerous than in the Eastern Goldfields Province (Fig. 3). Subordinate felsic volcanic or volcano-clastic units in mafic sequences also deserve attention as the deposits at Murrin and Mount Mulcahy illustrate. Further subsurface investigation is warranted at Anaconda (expecially northern shoot) and Mount Mulcahy.

The presence of prospective felsic rocks in the Southwestern Province of the Yilgarn Block should not be overlooked, although medium to high-grade metamorphism and strong deformation may make their recognition more difficult.

Volcanogenic copper-zinc deposits in the Canadian Precambrian seem to occur in groups with individual deposits forming a geometric progression in size (Boldy, 1977). Boldy (1977) concludes that relatively 'low risk' exploration in high density areas offered a good chance of finding a middle-sized deposit, whereas 'high risk' exploration in low density areas offered a better chance of finding a large deposit.

The Pilbara Block is well exposed and far more amenable to regional geochemical prospecting than the Yilgarn Block. Felsic volcanic rocks are of restricted occurrence and most surface indications of mineralization have been investigated. Systematic prospecting of the whole Whim Creek Group is warranted especially in poorly exposed areas. The existence of further ore shoots down plunge of the Whim Creek, Whundo-Whundo West and Yannery Hills copper-zinc deposits is a possibility which would be expensive to test thoroughly, as pattern drilling would be the only conclusive exploration method. Unfortunately the known ore shoots are not of great enough size or grade in the primary zone to encourage such a search for mineralization which, if present may not be shallow enough for open cut mining. The Chunderloo deposit, south-southwest of Meekatharra is a small-scale version of Yannery Hills, and as such deserves some exploration attention; better mineralization could be present down plunge. Subsurface testing of the primary copper-zinc mineralization at Evelyn and of the primary stockwork and massive mineralization at Breens has not been adequate, nor is the nature of primary mineralization at Copper Hills known. However it is doubtful from existing information whether anything but low-grade copper mineralization will be found at depth.

Felsic volcanic rocks are present in the eastern arm of the Hall Creek Province in the Olympio and Biscay Formations (Halls Creek Group) and to a lesser extent in the western arm of the province. Remapping of these formations is needed to define their constituents more accurately than has been done in the past. Indications of copper-zinc and copper mineralization are widespread in the Halls Creek Group. Though the intrusive gabbroid suites have potential for copper-nickel mineralization, upgrading by the mobilization of disseminated sulphides into massive shoots may be necessary to make them of economic worth. If so, then gabbroids which have suffered later metamorphism and deformation, or are close to persistently active tectonic zones (e.g. Halls Creek Fault Zone) may be more prospective.

Cupriferous mineralization is sporadically associated with felsic volcanic-volcaniclastic rocks in two other tectonic provinces. The Ashburton Formation in the northern Gascoyne Province and the "Axial Sequence" of the Glengarry Sub-basin (Nabberu Basin) are both in this category. More detailed lithological subdivision than on published maps would be a necessary prerequisite for exploration in these areas. In this context it is of interest that the major copper deposits in the Bangemall Basin (Kumarina, Ilgarari) lie in a meridianal zone which is most likely to have a basement of "Axial sequence" rocks and more or less reworked Archaean rocks (as seen in the Marymia and Sylvania Domes). Both of these basement components are cupriferous as illustrated by deposits at Thaduna,

TABLE 9. PUBLISHED RESOURCES OF COPPER AND ZINC IN WESTERN AUSTRALIA AND ESTIMATED STATE TOTALS

Company: deposit	Indicated and inferred resources of sulphides (Mt)	Grade (per cent) Cu	Grade (per cent) Zn	Indicated and inferred resources of supergene-oxidised mineralization (Mt)	Grade Cu %	Contained metal (t) Cu	Contained metal (t) Zn
EZ-Amax-Aztec							
Golden Grove	13.5	3.59	unstated			484 650	significant
Geometals-Carr Boyd-Conwest -Westralian Nickel -CRA							
Freddie Well	0.5	0.25	10.0			1 250	50 000
Peko-PMI							
Mt Angelo (North)	0.4	2.00				8 000	
Western Selcast-MIM							
Teutonic Bore	ca. 2.5	3.5	9.5			87 500	237 500
Whim Creek							
Whundo-West Whundo	ca. 2.0	2.0	1.3	0.048	7.4	43 550	26 000
Whim Creek-Texasgulf							
Mons Cupri	ca. 1.0		3.6	ca. 11.0 including sulphides	1.0	110 000	36 000
Whim Creek	ca. 1.0	1.51	unstated	1.65	1.68	42 800	
Totals	20.500			12.698		777 750	349 500
Totals including unpublished data	[1]134.460			35.269		1 469 000	606 400

1 Includes estimates for some large, low-grade deposits.

Wonyulgunna and Jimblebar. Regional economic evaluation of this zone in the Nabberu and Bangemall Basin is warranted. There is a good potential for small tonnages of medium to high-grade supergene copper mineralization of economic interest at Ilgarari.

More conceptually based exploration targets are: (a) syngenetic-diagenetic mineralization of the Zambian Copperbelt type in transgressive arenite-siltstone-dolomite-evaporite-carbonaceous pyritic shale sequences, and (b) epigenetic mineralization of the Keweenawan type in thick basaltic formations and associated pyritic shales. Candidates for the former are the Elgee Siltstone (Kimberley Basin), the Bungle Bungle Dolomite and Mount Parker Sandstone (Birrindudu Basin), Carr Boyd Range Group (Victoria River Basin), Bitter Springs Formation (Amadeus Basin) and perhaps the Duck Creek Dolomite (Hamersley Basin). Keweenawan type models could be erected for the Carson Volcanics, Hart Dolerite and Fortescue Group basalts.

CHAPTER 4

Kimberley Basin

SUMMARY AND CONCLUSIONS

The basin extends over some 160 000 km^2 and contains some 10 km of Lower Proterozoic arenite, lutite, basalt, basic and acid sills, and minor dolomite. Unconformably overlying the Lower Proterozoic sequence in the southern part of the basin are various mid-upper Proterozoic sedimentary rocks, which are some 6 km thick but of restricted extent. The basin sequence unconformably overlies the Lower Proterozoic rocks of the Halls Creek Province; this province effectively bounds the basin to the south. Stratigraphy is summarized in Table 10. Beds are sub-horizontal or gently deformed by open folds and normal faults throughout the bulk of the basin, only rocks adjacent to or as outliers within the Halls Creek Province are deformed more than this.

Copper mineralization is present as widespread, but low-grade and sporadic, stratiform occurrences and more rarely in quartz veins many of which appear stratabound (Plate 2). Most occurrences are recorded from the Elgee Siltstone, Pentecost Sandstone, Carson Volcanics and Hart Dolerite, but mineralization has also been found in the Warton Sandstone, Walshe Tillite, Mendena Formation, Fish Hole Dolerite and the Wotjulum Porphyry. Production is only recorded from a small mine in the last named formation, although attempts have been made to mine small amounts of cupriferous silver-lead mineralization emplaced in the Hart Dolerite at one locality.

The stratiform cupriferous mineralization in the Teronis Member of the Elgee Siltstone and the basal beds of the Middle Pentecost Sandstone has attracted most attention. Both horizons are very shallow water marine and arenaceous, but the mineralized part of the Teronis Member is calcareous. The beds are anomalous geochemically over a large area but visible mineralization is mainly restricted to the east. Best grades are in the range of 0.1-0.4 per cent copper over a few metres with very short strike lengths. Probably little more than 0.1 per cent is attainable over a workable thickness of 10 m and a strike length of a few kilometres. Detailed palaeogeographic analysis might yield target areas with potential for better grade mineralization. However more important requirements may be: (i) a more copper-rich basement, and (ii) the presence of evaporites in the sequence which might have provided higher concentrations from dispersed syngenetic copper.

The grades of stratiform mineralization in the siltstones of the middle Warton Sandstone in the Yampi Peninsula are more encouraging (up to 1 per cent copper over 5 m) with the possibility of strike lengths of several kilometres, although supergene redistribution of mineralization has taken place at least locally. Mineralization in other sedimentary formations is very restricted, one occurrence being recorded from siltstone of the Mendena Formation (possibly regionally anomalous in copper at a low level), and two from dolomite in the Walshe Tillite. The latter may result from circulating ground water which has leached copper from the underlying Elgee Siltstone.

The basalts of the Carson Volcanics may contain more copper than average mafic igneous rocks over the whole Kimberley Basin, but on limited evidence it appears that grades of interest (0.5-1.0 per cent copper) may be restricted to small areas of faulted and/or altered rock. There are no documented parallels to the widespread zones of alteration which are associated with copper mineralization in the Keweenawan basalts of Michigan, USA, but they may exist. Such alteration is associated with low-grade, burial-style regional metamorphism in Michigan (Jolly, 1974). If an analogy is sought for the Carson Volcanics, those parts of the formation within the Halls Creek Province (i.e. on the Mount Ramsay and Yampi Sheets) would be expected to be weakly metamorphosed, as well as mildly folded and fractured, in preference to flat-lying outcrops in the main Kimberley Basin. R. E. Smith (1975a, 1975b, 1976) has developed these concepts with reference to finding Keweenawan type copper deposits in the Fortescue Group basalts of the Hamersley Basin.

The Hart Dolerite is thickest on the margins of the Halls Creek Province where it may develop granophyric tops. Mineralization is apparently weaker than in the Carson Volcanics, and most occurrences are in quartz veins present in the zone marginal to the Halls Creek Province, which contain minor accessory amounts of copper minerals. The formation seems to have little potential for copper deposits of economic interest.

STRATABOUND MINERALIZATION IN SEDIMENTARY ROCKS (TYPE B)

INTRODUCTION

Copper deposits of this type in the Mendena Formation, Pentecost Sandstone and Elgee Siltstone were first described by Harms (1959) from the eastern margin of the basin. He suggested that the mineralization in the latter two formations was derived from dolerite intrusions although dolerite was absent at the Pentecost Sandstone locality (Campbellmerry). Regional mapping of the Ashton, Cambridge Gulf, Lissadell and Mount Elizabeth Sheets in 1963-1965 by the Geological Survey of Western Australia and the Bureau of Mineral Resources resulted in the discovery of two widely separated stratiform disseminated malachite occurrences (New York and Pentecost Range) on the opposite sides of the Menuairs (or 'Bindoola') Dome, both just above the base of the Middle Pentecost Sandstone (Roberts and others, 1966). Malachite was also noted from the Elgee Siltstone on the Ashton Sheet (Derrick, 1968) on the northwest flank of the Menuairs Dome (Bindoola Creek), and azurite from the same formation in the Chamberlain River valley in the southwestern part of the Lissadell Sheet (Plumb, 1968). An orientation stream sediment geochemical survey on the Lansdowne Sheet revealed that samples derived from the Teronis Member averaged 10 ppm copper versus 2 ppm copper for the rest of the Elgee Siltstone (Gellatly, 1967). In 1969 Planet discovered numerous copper occurrences in the Teronis Member (chloritic green siltstones) of the Elgee Siltstone, in the Chamberlain Valley between 16°25′S and 17°00′S (Lissadell Sheet and southeastern corner of Mount Elizabeth Sheet). This prompted a search for stratabound copper, mostly in the Teronis Member and the basal Middle Pentecost Sandstone, by other exploration companies including Tanks, Anglo American, CRA, WMC and Serem. Most copper occurrences in sedimentary rocks in the east Kimberley Basin are at these two stratigraphic levels in the eastern half of their outcrop (Plate 2, Figs 5 and 6).

TABLE 10. SUMMARY OF KIMBERLEY BASIN STRATIGRAPHY AND LOCATION OF STRATABOUND COPPER MINERALIZATION

Group	Formation	Mineralization and remarks
	Upper Proterozoic	
Louisa Downs Group	Lubbock Formation Tean Formation McAlly Shale Yurabi Formation Egan Formation	Group is restricted to Mount Ramsay Sheet, basal formation is glacial.
	unconformity	
Kuniandi Group	Mount Bertram Sandstone Wirara Formation Stein Formation Landrigan Tillite	Largely equivalent to Mount House Group; restricted to Mount Ramsay Sheet.
Mount House Group	Estaughs Formation Throssell Shale Traine Formation	Group restricted to west Kimberley region.
	Walshe Tillite	Erratic chalcocite nodules in dolomite at top (isolated).
	probable unconformity	
	Middle Proterozoic	
Glidden Group	Maddox Formation Forman Sandstone Matheson Formation Harms Sandstone	Unconformable on Carson Volcanics; very small basins on Mount Ramsay Sheet.
	unconformity	
	Lower Proterozoic	
Crowhurst Group	Hibberson Dolomite Collett Siltstone Liga Shale Hilfordy Formation	Largely equivalent to Bastion Group; both Groups restricted to East Kimberley region.
Bastion Group	Cockburn Sandstone Wyndham Shale	
	Mendena Formation	Isolated traces of copper mineralization.
Kimberley Group	*Pentecost Sandstone	Disseminated malachite in micaceous beds.
	*Elgee Siltstone	Copper and iron sulphides and copper carbonates in chloritic siltstones of Teronis Member.
	Warton Sandstone	Disseminated mineralization noted from Yampi Sheet.
	*Carson Volcanics	Copper sulphides and carbonates in amygdales, vugs, fractures; mostly in the lower basaltic flows.
	King Leopold Sandstone	
Speewah Group	Luman Siltstone Lansdowne Arkose Valentine Siltstone Tunganary Formation O'Donnell Formation	
Lower Kimberley Group equivalent	Revolver Creek Formation	Outliers of Kimberley Basin rocks within eastern arm of Halls Creek Province.
Speewah Group equivalents	Red Rock Beds Moola Bulla Formation	
Generally sill-like intrustions into the Speewah and Kimberley Groups.	Fish Hole Dolerite	Isolated malachite/azurite shows; intrudes Red Rock Beds.
	Wotjulum Porphyry	Cupriferous quartz veins (Yampi Sheet)
	*Hart Dolerite	Disseminated chalcopyrite; copper-bearing galena-quartz veins.

*Indicates formations containing widespread mineralization.

Other recorded occurrences are concentrated in the extreme west of the basin on the Yampi Sheet, where, during regional mapping in 1966 (Gellatly and Sofoulis, 1973), copper mineralization was recorded at two widely separated localities from the same stratigraphic level of the Warton Sandstone in the McLarty Range region. More occurrences in the Jap Bay Member of the Warton Sandstone were discovered by Amax in 1972. The formation is apparently barren in the rest of the basin.

Copper occurrences found by Harms (1959) in the Mendena Formation (Plants, Lissadell Sheet) and the Walshe Tillite (Police Creek, Mount Elizabeth Sheet) appear to be isolated examples.

Of all the occurrences described below in this section only Mount Edith East has been inspected by the author.

ELGEE SILTSTONE

GEOLOGY AND MINERALIZATION

The Elgee Siltstone is stratigraphically above the Warton Sandstone and below the Pentecost Sandstone (Table 10), and is extensive in the central and eastern Kimberley Basin but is restricted in distribution in the remainder (Plate 2). The formation becomes thicker and more silty when traced southwards, and contains carbonates in the southeastern part of the basin (Gellatly and others, 1970). Explanatory notes on the Lansdowne (Gellatly and Derrick, 1967), Lissadell (Plumb, 1968), Mount Elizabeth (Roberts and Perry, 1970) and

Mount Ramsay (Roberts and others, 1968) Sheets describe the bulk of the formation as red-brown siltstone with interbeds of flaggy, quartz and feldspathic sandstone. A distinctive basal member of the formation comprising grey-green shale and micaceous siltstone with interbeds of dolomite and sandstone was recognised and named the *Teronis Member*. The member appears to be absent on the Drysdale Sheet, west of the Durack River on the Ashton Sheet, and west of the Chapman River on the Mount Elizabeth Sheet (Klaric, 1975). The whole formation generally occupies valleys and is poorly exposed, particularly the Teronis Member. Commonly only the upper Elgee Siltstone is visible because it crops out in the lower slopes of the prominent scarp features formed by the overlying blocky quartz sandstones of the Pentecost Sandstone.

The formation reaches a maximum thickness of 350 m east of 126°E on the Mount Ramsay Sheet, where it is folded and locally divisible into four sandstone horizons and three purple shaly horizons (Serem, 1971), but is apparently devoid of copper. Average thickness on the Lansdowne, Lissadell and Mount Elizabeth Sheets is 180 to 210 m with the Teronis Member being 15 to 23 m thick, but the formation thins farther north and when traced from east to west on the Ashton and Drysdale Sheets. On the Medusa Banks Sheet (Plumb and Perry, 1971) the formation thins from 137 m in the south to 82 m in the north and becomes sandier northwestwards. Elgee Siltstone also crops out on the Lennard River (172 m thick), Charnley (18 m) and Camden Sound (40 m) Sheets in small areas, and forms an extensive folded and partly metamorphosed outcrop on the Yampi Sheet (35 to 480 m). No copper has been recorded in these regions, though malachite-stained green shale occurs in the Teronis Member near Halls Point (15°40′S, 124°23′E) on the Camden Sound Sheet (I.M. Paltridge, pers. comm., 1976). Gellatly and others (1970) note the presence of halite pseudomorphs in this area.

In the Chamberlain Valley area, Planet (Bruinsma, 1970) subdivided the Elgee Siltstone into three members (including the Teronis Member as previously mapped), and further subdivided the Teronis Member into four units (Table 11). Copper mineralization is restricted to the Teronis IV unit which consists of calcareous sandstones, shales and siltstones and dolomitic siltstones whose mineralogy is quartz, sodic plagioclase, illite, iron-rich chlorite, dolomite, calcite, copper sulphides, malachite and pyrite (Bruinsma, 1970). The dolomitic siltstone contains dolomitized, laminated algal stromatolites, some of which are fragmented, and some oolitic sandy dolomites. These features in conjunction with the presence of mud cracks, rain drop imprints and salt casts elsewhere in the Teronis Member are good evidence of a very shallow water, near shore marine environment (Owen, 1970). Flute-cast orientations (Owen, 1970) and a northward thinning (Plumb, 1968, p. 13) suggest that the shoreline was to the northeast of the Chamberlain Valley when the member was being deposited.

There is not sufficient information to indicate the geometry of the depositional basin of the Elgee Siltstone elsewhere in the Kimberley Basin, though predominant current directions from the northwest were observed by Gellatly and Sofoulis (1969 and 1973) on the Drysdale and Yampi Sheets respectively, and reported by Tanks from the Menuairs Dome area.

Although the data are limited it is evident that the Teronis IV unit is regionally anomalous in copper, but concentrations along strike are variable with average values probably being in the range 200 to 350 ppm copper. Assay results from surface channel samples appear to be comparable with values from drill core at the same site, hence surface or supergene enrichment is probably of little importance.

The sulphide mineralization appears to be syngenetic and/or diagenetic in origin, having formed in a near-shore environment. The source of the copper is unknown but it is possible that cupriferous mafic igneous rocks of the Carson Volcanics or Hart Dolerite may have been the source if exposed in a landmass to the east. The copper could have been absorbed by clay minerals, which were trapped by algal stromatolite mats then precipitated as sulphides by decayed algal material (cf. Mendelsohn, 1976, p. 660). There are several problems with this simplistic model. Algal dolomites and associated rocks in the Teronis II unit are

TABLE 11. STRATIGRAPHY OF THE ELGEE SILTSTONE IN THE CHAMBERLAIN VALLEY AREA, EAST KIMBERLEY REGION

BMR-GSWA	Planet (Bruinsma, 1970)		
PENTECOST SANDSTONE			
UNNAMED UPPER MEMBER	UPPER ELGEE SILTSTONE MEMBER	15 m	Red-grey feldspathic sandstone
	MIDDLE ELGEE SILTSTONE MEMBER	143 m	Red-brown siltstone with red shale and sandstone interbeds, green shales at base
TERONIS MEMBER	LOWER ELGEE SILTSTONE OR TERONIS MEMBER	*Teronis IV 8-12 m	Green shale, siltstone, sandstone, calcareous and dolomitic sandstone, siltstone and dolomite (commonly algal)
		Teronis III ca. 20 m	Red-brown siltstone with minor red shale
		Teronis II	Grey-green shale with siltstone and fine-grained sandstone interbeds, some oolitic sandy, and algal dolomite
		Teronis I ca. 14 m	Grey-green sandstone with minor red-green siltstone and shale at base
WARTON SANDSTONE			

*copper mineralization is confined to this unit

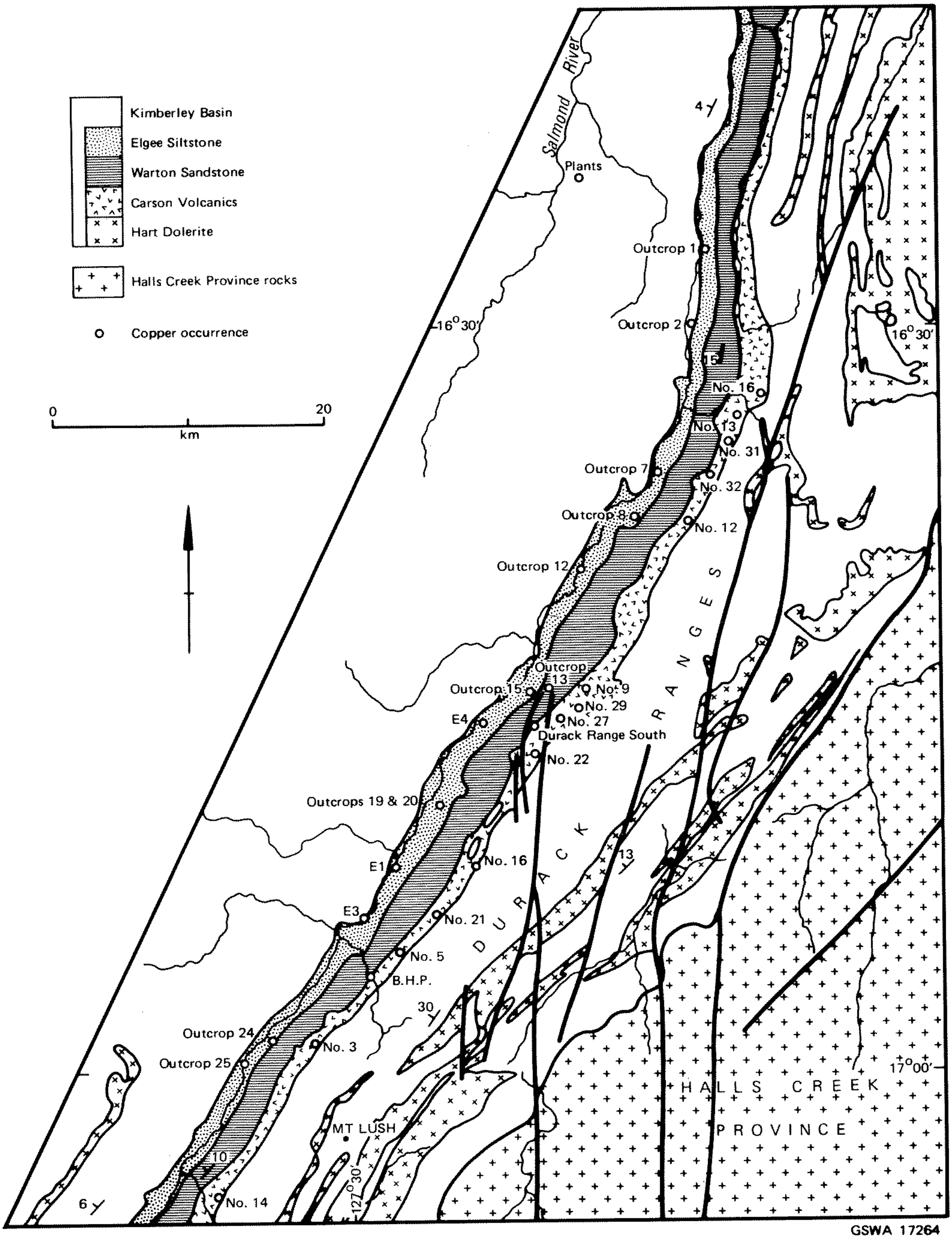

Figure 5. Copper occurrences in the Chamberlain Valley and Durack Ranges area

very similar lithologically to Teronis IV, but are not mineralized. If bacterial reduction of sea water sulphate is proposed as the major source of sulphur, the rocks would be expected to be rich in organic matter (e.g. graphite) which they are not. Insufficient data are available for more informed comment on ore genesis. The depositional environment at Chamberlain Valley has several features in common with the Zambian copperbelt but the important ingredients missing appear to be (i) a copper-rich basement (source area) and (ii) the presence of evaporites and hydrocarbon-rich rocks in the sequence (brine source and reducing agent).

CHAMBERLAIN VALLEY

This area (16°oo'S to 17°25'S) was investigated by the Planet Group of companies in the period 1968-1972 being joined by Anglo American from late 1970 on. Planet formed a new company in late 1970, called Durack Mines, to conduct exploration in the area. Access is possible via the abandoned Elgie Cliffs homestead. Exploration effort concentrated on the southern half of the north-northeast-trending strike valley (16°25'S to 17°00'S) where eleven copper occurrences were found in the grey-green sedimentary rocks of the Teronis Member exposed beside the Chamberlain River (Fig. 5). The beds dip west-northwest at 8 to 20 degrees. Mineralization at the surface is present as finely disseminated (generally < 1 mm) chalcocite, covellite, digenite, chalcopyrite, bornite and pyrite in grey-green and dark grey calcareous siltstones and sandstones, and as malachite in shales where it has been redeposited after leaching from the calcareous rocks (Hawley, 1971). The sulphides also occur in stringers or concentrated at the base of graded beds and in minute contorted siltstone or sandstone dykes in shales. According to Hawley (1971) the mineralization is best developed in the topmost 1.5 m of the Teronis IV unit and is commonly restricted to calcareous siltstones. Pyrite and chalcopyrite predominate in the north whereas bornite and chalcocite become the important sulphides in the central and southern parts of the area.

In 1970 a series of ten vertical diamond holes totalling 924 m were drilled by Planet down dip from some of the mineralized outcrops found over a 20 km strike length. Drillhole numbers DDH 11, 18, 19 and 21 were drilled at site E1 (16°52'S, 127°32'E), DDH 14 and 20 at site E3 (16°53'30''S, 127°42'E), DDH 15 at site E2 (16°55'S, 127°30'E), DDH 22 at outcrop 25 (16°59'30''S, 127°26'E), DDH 16 at outcrop 20 (16°49'30''S, 127°34'E) and DDH 17 at site E4 (16°46'S, 127°36'E). Terminal depths ranged from 60 to 156 m and the mineralized zone was intersected at vertical depths of 3.5 to 98 m. The best intersections were at site E1 where DDH 11 assayed 982 ppm copper over 9.48 m and DDH 19 (sited about 400 m north-east of hole 11) assayed 967 ppm copper over 10.55 m at depths between 43.9 and 65.8 m. All other drillholes assayed between 157 and 453 ppm copper over intervals of 7.0 to 1.3 m.

In 1971 Anglo American (Orr, 1971) drilled 34 percussion drillholes over a 74 km strike length of the Teronis IV unit (between 16°30'S and 17°00'S). This unit was intersected at depths ranging from 8.8 m to 43.6 m. No enrichment of copper with depth was found and a mean assay value of 237 ppm copper resulted over a mean thickness of 9 m. Mean values for individual holes ranged from 188 to 1053 ppm copper over drilled thicknesses of 5.5 to 14.6 m. The highest values over 1.8 m from each hole were 2 942 and 1 626 ppm copper, the remainder were less than 800 ppm copper.

MENUAIRS DOME

The Menuairs Dome (also known as the Bindoola Dome) is an elongate, gentle domal structure exposing a core of Warton Sandstone which is some 35 km long (east-northeast) and up to 20 km wide. Access to this area can be gained from the Wyndham-Gibb River graded road. The bulk of the structure is on the adjoining southwestern and southeastern corners of the Cambridge Gulf and Ashton Sheets respectively, with the southern margin occurring on the Lissadell and Mount Elizabeth Sheets. Bindoola and Palmer Creeks have etched out the Elgee Siltstone which is poorly exposed below the rimming scarp of the basal Pentecost Sandstone.

Derrick (1968) recorded malachite coatings associated with gypsum on bedding planes of fissile red-brown siltstone and mudstone where the Elgee Siltstone is cut by a small north-northwest-trending fault at Bindoola Creek (15°51'40''S, 127°27'00''E). Malachite also occurs in a quartz-cemented fault breccia.

During a regional geochemical survey of the east Kimberley Basin, CRA (Klaric, 1971a) located two outcrops of malachite-bearing green-grey shale-siltstone of the Teronis Member on opposite sides of the dome. A chip sample at the Menuairs Dome Southwest occurrence (15°57'00''S, 127°28'30''E) assayed 715 ppm copper, and a composite chip sample at the Menuairs Dome Northeast occurrence (15°50'00''S, 127°36'30''E) assayed 905 ppm copper.

In the early 1970s Tanks carried out a regional search for stratabound copper in the Elgee Siltstone and selected the Menuairs Dome for more detailed appraisal. The Teronis Member was subdivided into three units, the upper and lower units being barren. In the middle unit fine-grained disseminations of chalcopyrite and bornite occur in chloritic siltstones and shales, and fine-grained feldspathic sandstones. Mineralization may be concentrated along bedding planes and has a consistent vertical distribution, though some chalcopyrite occurs in fractures. Graphite is associated with the chalcopyrite. The more arenaceous or carbonate-bearing rocks contained only very small amounts of copper. Fourteen diamond drillholes disclosed only sparse mineralization of no economic importance. Oxidation is present to a few metres below surface thereby making secondary enrichment an unlikely phenomenon.

LYNE RIVER AREA

This area lies on the northeast flank of the Elgee Siltstone structural basin, north of Wyndham and west of Cambridge Gulf, where dips are gently south or southwest and a series of north-northwest-trending faults repeat the sequence. Ready access to the localities described is only feasible by helicopter. Malachite flakes along bedding planes and joints in green shales and siltstones of the Teronis Member were found over an extensive strike area by CRA in 1971 (Klaric, 1971a). The main occurrence at Lyne River (14°55'S, 127°58'E) is an exposure of malachite-stained green shale with glauconitic sandstone at the base which assayed 442 ppm copper over 2.4 m; a composite sample of the green shale only, contained 750 ppm copper. Similar malachite-stained shale 2.5 km to the north-northwest assayed 380 ppm copper, and a green shale 3.5 km along strike to the south-southeast contained 319 ppm copper. At Lyne River North (14°48'S, 127°54'30''E) a 4.6 to 6.1 m thick section of the member is exposed. A channel sample over 0.6 m thickness of green cupriferous siltstone and shale with ripple marks and load casts assayed 1 200 ppm copper. Green shale 4 km along strike to the southeast contained 890 ppm copper in a grab sample.

To the northeast of this area a 2.13 m thick section of green-grey cupriferous shale at Helby River (14°44′30″S, 128°05′00″E) assayed 1 300 ppm copper. Along strike to the west at Helby River West (14°42′20″S, 127°58′00″E) 2.1 m of green and dark grey shale with malachite staining assayed 535 ppm copper, whereas a 6.1 m thick section of green-grey micaceous siltstone-shale with load casts contained 389 ppm copper.

These occurrences further demonstrate the regionally cupriferous nature of the Teronis Member in the eastern parts of the basin. The mineralization lacks economic potential in the apparent absence of any structures or modifying agents (e.g. metamorphic or supergene processes) that might have further concentrated the copper.

OTHER OCCURRENCES

At Teronis Yard (17°17′S, 127°15′E), 37.5 km east of Tableland homestead, the Teronis Member dips at 5 to 10 degrees to the northwest. The Chamberlain River flows northwest through the Warton Sandstone outcrop in the Teronis Gorge, which appears to be controlled by a master joint intruded by a dolerite dyke. Harms (1959) describes chalcocite veins up to 6 mm thick and 30 cm long in the baked contact zone of the dyke where it cuts the 'Elgee Shale'. Secondary copper carbonates also stain the shale up to 30 cm from the contact. Harms assumed that the copper was derived from the dolerite, but from his description it seems more likely that disseminated mineralization within the Teronis Member has been mobilized and concentrated marginal to the dyke.

Some 47 km west-southwest of Teronis Yard, CRA (Klaric, 1971a) discovered cupriferous (malachite) green micaceous shales of the Teronis Member at Little Fitzroy River (17°23′30″S, 126°49′00″E). An assay of 750 ppm copper was returned from a channel sample over 0.6 m thickness.

Outcrops of the Teronis Member exposed in the banks of the Pentecost River (15°58′00″S, 127°55′00″E) consist of siltstone, sandstone and shale with malachite. Assays of 1 200 ppm copper over 2.1 m thickness and 1 400 ppm copper over 1.2 m thickness were obtained by CRA (Klaric, 1971b). Thirty kilometres west-northwest of Kununurra at Spring Creek (15°43′00″S, 128°28′30″E), green shale of the Teronis Member assays 827 ppm copper (Klaric, 1971a).

PENTECOST SANDSTONE

GEOLOGY

Over most of the Kimberley Basin this formation has been divided into Lower, Middle and Upper Members, the bulk of which consist of ripple-marked and cross-stratified, blocky or flaggy, fine to medium-grained quartz sandstone. The Pentecost Sandstone has a similar areal distribution to the Elgee Siltstone (Plate 2): the major outcrop is in the central and eastern parts of the basin where it is 900 to 1 100 m thick, thinning in the north (760 m on Drysdale Sheet; 670 m on Medusa Banks Sheet) and the extreme south (650 m on Mount Ramsay Sheet). Gellatly and others (1970) found a predominance of current directions from the north and northwest. The base of the Middle Member (120 to 400 m above the Teronis Member) consists of a distinctive shale-siltstone-glauconitic sandstone bed which is anomalous in copper on a regional scale in the eastern part of the basin, over a similar area to that covered by the Teronis Member copper occurrences. Green-grey shale and siltstone, which may be micaceous, form a poorly exposed sequence some 30 m thick overlain by the purple-brown ferruginous and glauconitic sandstone which forms prominent cuestas. The copper mineralization is commonly restricted to the green shale-siltstone sequence; it occurs as disseminations of malachite on bedding planes and in fractures. In 1971 Anglo American prospected the entire outcrop of Lower-Mid Pentecost Sandstone contact (1 140 km strike length) in the central and eastern Kimberley Basin (Orr, 1971). The best appearing surface copper mineralization was found to be in the Menuairs Dome area.

MENUAIRS DOME

The New York occurrence (15°59′10″S, 127°26′30″E) was described by Roberts and others (1966) as grey-green flaggy to fissile laminated micaceous siltstone less than 1.5 m thick, which contains clusters of malachite flakes in the bedding and cross fractures. The rock consists of quartz, chlorite, plagioclase, microcline and accessory graphite. A grab sample assayed 0.36 per cent copper. Klaric (1971a) took a composite chip sample of green shale from the same locality: this sample assayed 370 ppm copper.

Mineralization seems to be considerably better at the eastern end of the dome in the Pentecost Range area. The occurrence originally described by Roberts and others (1966) is located at 15°48′10″S, 127°46′40″E and contains malachite on bedding planes in the lowest 1.5 m of the fissile siltstone-sandstone sequence. Klaric (1971b) described an occurrence 1.5 km to the north as the largest cupriferous outcrop in the Pentecost Range: here visible malachite occurs over 600 m of strike. Assays of 3 200 to 3 700 ppm copper were returned from 0.6 m thickness of siltstone and 1.2 m of sandstone; this area was also examined by Anglo American. Green micaceous shale with an 0.6 m thick bed containing malachite was recorded by Klaric (1971a) 2 km south of the occurrence of Roberts and others (1966): this shale assayed 668 ppm copper over 2.44 m. A grab sample taken 6 km south of the occurrence described by Roberts and others (1966) assayed 846 ppm copper.

On the northern flank of the dome the author examined an occurrence at Mount Edith East (15°48′00″S, 127°42′00″E) of disseminated malachite in 10 to 30 cm thick beds of red-brown, fine-grained quartz sandstone with mudstone clasts, which overlies green chloritic and micaceous siltstones and flagstones. At Mouth Edith North (15°46′20″S, 127°39′00″E), 8 km along strike to the west, Klaric (1971b) reported a 300 m strike length of cupriferous siltstone assaying 1 000 ppm copper over a 1.8 m thickness. At Durack River (15°49′30″S, 127°24′30″E) a malachite show was reported by Anglo American (Orr, 1971).

Following a programme of soil geochemical traverses at 800 m line spacings, along the northern, eastern and southern flanks of the dome, Anglo American (Orr, 1971) decided to drill where anomalies greater than 100 ppm copper were encountered over two or more adjacent lines. At twenty sites eight percussion and eighteen diamond drillholes intersected the target horizon at between 23 and 69 m drilled depth. Drilling was concentrated on 40 km of strike between the Pentecost Range and the Durack River (15°45′S, 127°30′E). The other main sites were at Grimwood Creek (16°01′30″S, 127°35′00″E) where a 4.8 km strike length of contact was drilled. The mean copper assay for the 26 holes was 481 ppm over 3.7 m, ranging from 118 to 1 249 ppm over 1.8 to 7.3 m drilled thickness, the best values being in the range 1 000 to 2 000 ppm over 0.46 to 1.8 m. Visible mineralization at the surface did not generally persist at depth: at one locality grab samples assayed 0.75 per cent copper, a chip sample over 3.7 m returned 0.24 per cent copper, whereas the same horizon in drill core assayed 0.05 per cent copper over 6.1 m (at drilled depth of 32 to 38 m). Orr (1971) proposed that surface enrichment of syngenetic copper minerals in the horizon has taken place because of ground water movement along bedding planes above the relatively impermeable topmost quartzite of the Lower Pentecost Sandstone.

CAMBRIDGE GULF AREA

Five occurrences of cupriferous green shale-siltstone at the base of the Middle Pentecost Sandstone are recorded by Klaric (1971a, 1971b) over a 50 km strike length west of Cambridge Gulf. They are described from south to north. A helicopter would be needed for ready access.

The Paps occurrence (15°14′30″S, 128°40′00″E) is immediately southwest of the scarp formed by the Lower Pentecost Sandstone: The sequence is as follows:

TOP	3. purple, ferruginous green-spotted (glauconite?) sandstone	4.6 m
	2. white, siliceous sandstone	6.1 m
	1. green shales with malachite	4.6 m
	Lower Pentecost Sandstone	

A channel sample from the 4.6 m thick green shales assayed 0.24 per cent copper and a grab sample 0.72 per cent copper. These values are the highest obtained by CRA during their regional geochemical survey of the eastern Kimberley Basin in 1971. Klaric (1971a) states that the cupriferous shale could extend over 0.65 km^2 but may thin out or grade laterally into green, chloritic quartz sandstone (Klaric, 1971b).

At Terrace Hill North (15°11′S, 127°59′E) green micaceous shale-siltstone 9 m thick contains a 3 m thick malachite-stained section which assayed 1 120 ppm copper. The Mount Fraser West occurrence (15°05′S, 127°59′E) is 11 km farther north: here green micaceous shale-siltstone contains 745 ppm copper over 1.5 m. A 3 m thick section of similar rock at Mendena Creek (15°01′30″S, 127°58′00″E) assayed 376 ppm copper. At Mount McMillan South (14°51′30″S, 127°53′30″E) a 15.24 m thick section of green shale-siltstone with traces of malachite returned 105 ppm copper, whereas a green and red shale-siltstone section of similar thickness assayed 295 ppm copper.

OTHER OCCURRENCES

Harms (1959) discovered thin cupriferous quartz veins in the middle part of the Middle Pentecost Sandstone at Campbellmerry (16°10′40″S, 127°35′10″E). The veins contain malachite and cuprite and there is copper staining on joints in the sandstone at Grimwood Gap nearby. Klaric (1971b) noted that the (main?) vein strikes northwest, is 9 m wide in the northwest and 1 m wide in the southeast and contains copper minerals over a 275 m length. One composite sample over 9 m assayed 2.6 per cent copper. He also established the feasibility of four wheel drive access to the occurrence.

Vuggy quartz with malachite occurs in a fracture in chloritic sandstone of the Middle Pentecost Sandstone at Maggy's Creek (15°40′40″S, 128°15′10″E), immediately north of the Great Northen Highway (Klaric, 1971a). At Mundurrul River (16°17′00″S, 123°38′50″E) a copper occurrence is present in the middle section of the Pentecost Sandstone (undivided here) on the steeply north-dipping southern limb of a syncline.

WARTON SANDSTONE

GEOLOGY

Mapping of the Yampi Sheet in 1966 and 1967 (Gellatly and Sofoulis, 1973) resulted in the subdivision of the Warton Sandstone on Koolan Island into three members which can be traced throughout most of the northwestern Yampi Peninsula (Gellatly, 1972). The subdivision is as follows:

	Elgee Siltstone	
TOP	3. Arbitration Cove Sandstone Member	70-300 m
	2. Jap Bay Member	ca. 40 m
	1. Blinker Hill Sandstone Member	75-270 m
	Carson Volcanics	

The Jap Bay Member contains copper mineralization in the McLarty Range area (Fig. 6). The member consists of siltstone with thin interbeds of fine-grained feldspathic sandstone (Gellatly, 1972). In the McLarty Range area a laminated ferruginous chert up to 15 m thick is present in the member. These rocks are metamorphosed to phyllite and quartzite and deformed by open folds trending northwest. Dips range from 25 degrees to the vertical.

Access into the area is only feasible by helicopter at present.

MINERALIZATION

Two copper occurrences 15 km apart but at the same stratigraphic level were noted by Gellatly and Solfoulis (1973). Subsequently regional geochemical work in the McLarty Range area by Amax (Gellatly, 1972) disclosed a further seven occurrences at a similar stratigraphic level (Jap Bay Member). These occurrences and the two original discoveries (2 and 9) have been numbered from 1 to 9. The mineralization is present as disseminated malachite, cupriferous ferruginous nodules and small lenticular gossans. It is associated with ferruginous banded chert and siltstone (phyllite): supergene redistribution has probably taken place into adjacent previously unmineralized siltstone. Surface outcrops are strongly leached and visible copper was only located in eroded areas (Gellatly, 1972). Occurrences 1, 3 and 7 were considered by Gellatly (1972) to hold the best potential for economic mineralization. Gellatly (pers. comm. 1977) considers that the mineralization orginates through replacement of pyrite in the siltstone by migrating copper-bearing solutions derived from the underlying basalts and basic tuffs of the Carson Volcanics. He regards the style of mineralization as comparable with that at White Pine in Michigan, U.S.A.

At the McLarty Range 1 occurrence (16°21′00″S, 123°53′30″E) the mineralized phyllitic siltstone is 15 m thick and is 70 to 85 m above the base of the Jap Bay Member. The 15 m thickness assayed 0.78 per cent copper and the top 4.5 m returned 1.07 per cent copper. Goethitic nodules present at the base of the mineralized zone contain around 1 per cent copper. Small lenticular cupriferous gossans are present at McLarty Range 2 occurrence (16°22′E, 123°56′E): one gossan 5 m long and 0.6 m wide assayed 2.2 per cent copper from one chip sample. Traces of malachite are found in banded ferruginous chert at McLarty Range 3 occurrence (16°24′E, 123°59′E), and a chip sample over 3 m assayed 0.25 per cent copper. The main surface mineralized zone here is below the chert. Stream sediment geochemical anomalies suggest that the mineralized zone may extend from 3 km along strike. A channel sample over 1.5 m at McLarty Range 4 occurrence (16°25′00″E, 124°00′30″E) assayed 0.8 per cent copper.

At McLarty Range 5 occurrence (16°25′00″S, 124°01′30″E) siltstone and fine-grained sandstone exhibit a surface veneer of malachite over a 3 m thickness; a colluvial sample assayed 320 ppm copper. A similar rock at McLarty Range 6 (16°25′S, 124°02′E) contained 750 ppm copper in a colluvial sample. Two mineralized zones were recognized at McLarty Range 7 occurrence (16°24′00″S, 124°01′40″E). An upper, low-grade zone is 3 m thick and consists of chert and cherty sandstone with ferruginous laminae. This section assayed 1 250 ppm copper. A lower, higher grade zone of grey siltstone with small, irregularly distributed malachite-rich lenses is 1.5 m thick. A channel sample assayed 3.3 per cent copper over 2.5 m. Most of the copper is contained in arenaceous nodules replaced by malachite and a secondary copper sulphide. Mineralization decreases along strike from this locality. At McLarty Range 8 occurrence (16°22′30″S, 124°00′30″E) minor copper staining is present over a 16 m thickness of grey and red-brown siltstone which assays 1 500 ppm copper. The mineralized zone underlies a banded chert. At McLarty Range 9 occurrence (16°27′S, 124°02′E) mineralized siltstone assayed 900 ppm copper over 5 m and contains scattered goethite nodules (not included in channel sample), one of which assayed 3.2 per cent copper.

The surface grades of this mineralization are encouraging taken with the thicknesses and possible strike lengths of the mineralized zone(s).

OTHER OCCURRENCES

MENDENA FORMATION

Harms (1959) described minor veinlets of copper carbonate and oxides and chalcocite in siltstone at Plants (16°24′S, 127°40′E) immediately south of Plants homestead. The veins are less than 1.3 m long and up to 7.5 cm wide. Plumb (1968) recorded copper carbonate flakes on joints from the same locality. Klaric (1971a) described the host rocks as flat-lying, green-grey siltstone, with traces of malachite present along fissile partings and in a cross-cutting fracture filled with brecciated shale. A 15 m thick section of the siltstone assayed 257 ppm copper.

During regional reconnaissance in the east Kimberley region Klaric (1971b) noted that random grab samples from the Mendena Formation over a wide area assayed 100 to 200 ppm copper. The formation thus appears to be regionally anomalous in copper at a low level. The occurrence at Plants is perhaps the result of local mobilization of syngenetic copper by ground water and does not appear to be of any economic significance.

WALSHE TILLITE

The Police Creek occurrence (16°48′S, 126°26′E) was discovered by Harms (1959) in the upper part of the flat-lying Walshe Tillite where shales grade laterally into limestone. Near the base of this limestone is a 15 cm thick band of pink dolomite containing chalcocite nodules up to 5 cm by 2.5 cm in size and secondary copper carbonate coatings on joints. The nodules occur erratically over an 8 km strike (Harms, 1959).

Some 7 km to the east-southeast at the Traine River occurrence (16°49′30″S, 126°29′30″E) Klaric (1971a) found blocks of malachite-stained pink dolomite. A grab sample assayed 5 070 ppm copper. A detailed drainage sampling survey of the west fork of the Traine River failed to produce significant results.

This mineralization seems to be isolated and of no economic importance. Klaric (1971a) suggested that the copper could be recycled from the Elgee Siltstone which is unconformably overlain by the Walshe Tillite in this area. The area is in pastroal country of moderate relief and vehicular access should be feasible.

STRATABOUND MINERALIZATION IN MAFIC IGNEOUS ROCKS (TYPES B AND C)

CARSON VOLCANICS

GEOLOGY

The Carson Volcanics underlie the Warton Sandstone and overlie the King Leopold Sandstone (Table 10). Outcrop of the formation is most abundant in the western half of the Kimberley Basin. Average thicknesses range from 100 to 250 m in the east, 300 to 700 m in the centre, to 500 to 700 m in the west. A maximum thickness of 1 140 m in the northeastern part of the Yampi Sheet (Gellatly and Sofoulis, 1973) corresponds with a thick pyroclastic pile. Fresh and altered two pyroxene tholeiitic basalts make up the bulk of the formation; feldspathic and quartz sandstone interbeds occur throughout and the upper part of the formation in the centre of the basin consists of micaceous siltstone and shale. In the Durack Ranges up to four basalt flows with clastic interbeds occur. Agglomerates and tuffs are present locally in the southern and western parts of the basin. Amygdaloidal basalts are prevalent in the lower section of the formation. The amygdales are 0.1 to 5 cm in size and contain calcite, chlorite, quartz, epidote and chalcedony plus minor amounts of chalcopyrite, malachite, pyrite and hematite. Sulphides are also found in small epidote-quartz veinlets and disseminated in mafic agglomerates.

MINERALIZATION

Disseminated copper mineralization is widespread in the lower, amygdaloidal basalt flows, and has been recorded from every 1:250 000 sheet in the basin with the exception of Cambridge Gulf and Medusa Banks. The distribution of the occurrences shown (Plate 2) cannot be taken as an accurate indication of the distribution of mineralization above 'background levels'. Systematic prospecting of the formation has not been carried out except along the eastern outcrop (by Planet principally) on the Lissadell and Lansdowne Sheets (Durack Range area), but it appears possible that copper contents might be higher in this area as they seem to be in the Elgee Siltstone. Planet discovered thirty-four, mainly stratiform, occurrences in the Durack Ranges comprising the following types (in decreasing order of abundance):

(i) disseminations and veinlets of malachite, chalcocite, chalcopyrite and bornite in the tuffaceous top of the second basalt flow (from base) and/or in the overlying shale and chert;

(ii) copper carbonate disseminations along bedding planes or joints in sandstone interbeds amongst the flows;

(iii) copper carbonates, sulphides and oxides as veinlets and disseminations in fractured, faulted or epidotized basalt; and

(iv) copper carbonates and sulphides as veinlets and disseminations in the lowest amygdaloidal basalt.

There is little information about the nature of occurrences elsewhere in the basin, but several are disseminated chalcopyrite and pyrite in amygdaloidal basalt and one is in epidotized basalt (Cape Bougainville). None of the occurrences described below have been inspected but the common style of mineralization has been observed in the West Kimberley region.

DURACK RANGES

Here the Carson Volcanics dip at 10 to 15 degrees to the west-northwest and form a weakly developed strike valley separated by the cuesta of the Warton Sandstone from the Chamberlain Valley to the west, and bounded by the dip slopes of the King Leopold Sandstone to the east. The occurrences are grouped into types as detailed above, then described from north to south. Details are from Planet (1971). Follow-up work was undertaken in 1971 on selected prospects by Anglo American (Orr, 1971) in joint venture with Durack Mines (Planet originated company).

Type (i) occurrences: Disseminated malachite and chalcocite are present in black silicified tuff at the Number 16 show (16°32′30″S, 127°47′40″E). Immediately to the south Orr (1971) described an 'andesite' flow mineralized throughout (sulphides), which was tested by five percussion drillholes totalling 214 m. One hole intersected 38.4 m of basalt assaying 434 ppm copper including a 1.8 m section returning 1 612 ppm copper; the remaining holes yielded lower values. A grab sample assayed 7.8 per cent copper. At the Number 27 show (16°46′00″S, 127°39′00″E) malachite and chalcocite occur irregularly along a 100 m strike in the tuffaceous top of the second basalt flow. Chalcocite is found in masses up to 25 cm by 12 cm by 12 cm in size. A weaker occurrence of similar style is present 2.3 km along strike to the northeast. The Number 22 show (16°47′20″S, 127°38′50″E) exhibits chalcocite, chalcopyrite and bornite sporadically over 100 m of strike in the same tuffaceous band. Quartz-feldspar veins in the basalt are also cupriferous. Chalcocite and malachite occur irregularly over 30 m of strike at the same stratigraphic level as Number 6 show (16°51′30″S, 127°35′30″E) where chalcocite is also found in the overlying shale. The tuffaceous band at Number 21 show (16°52′00″S, 127°34′40″E) contains sporadic chalcocite and malachite over 183 m of strike. A similar but weaker occurrence is 2.75 km along strike to the south-southwest. The mineralized strike length at Number 5 show (16°54′40″S, 127°32′30″E) is 120 m and the cupriferous zone is up to 0.46 m thick. The BHP show (16°56′30″S, 127°31′00″E) was considered by Planet (1971) to be the best show at this stratigraphic horizon, the mineralized zone extending over an outcrop area of 180 m by 30 m, and commonly being 15 cm thick. Seven costeans and a large diameter percussion drillhole were put in by BHP. The mineralized shale at this show was tested over 1 100 m strike length by percussion drilling (5 holes totalling 501 m), but the best assay was 651 ppm copper over 1.8 m, other values were less than 400 ppm copper (Orr, 1971). At the Number 3 show (16°59′00″S, 127°28′30″E) malachite is found irregularly over 100 m or so strike length in the tuffaceous top of the second basalt flow. Malachite occurs in a similar situation in a 12 cm thick tuffaceous band dipping north at 2 to 6 degrees at the Number 1 Copper Prospect (17°28′30″S, 126°51′00″E) which is 100 km distant from the main area being described.

In the main area of occurrences the top contact of the second basalt flow is intermittently mineralized along a 45 km strike length.

Type (ii) occurrences: At the Number 13 show (16°33′40″S, 127°46′30″E) sparse malachite occurs over a 15 m square area on bedding planes in a 60 cm thick, cross-stratified, fissile sandstone containing muscovite, chlorite and glauconite (?). This sandstone occurs between two basalt flows in the north (where the sequence is simpler), and the mineralization is 6 m above a shale horizon. Malachite and azurite are disseminated on bedding planes and joints in chloritic sandstone below this shale horizon at Number 31 show (16°34′30″S, 127°46′00″E). The mineralization is seen over 100 m strike of sandstone outcrop. Malachite at a similar stratigraphic level occurs at Number 32 show (16°32′50″S, 127°45′30″E) and at Number 12 show (16°38′00″S, 127°44′30″E) where, in addition to malachite patches in sandstone along 210 m strike, thin quartz veins parallel to the bedding (in shale) contain quartz, specularite and malachite in small vugs. Further occurrences in sandstone have been found 1.8 km and 2.7 km along strike to the south-southwest of Number 12 show. At Number 29 show (16°45′30″S, 127°39′40″E) malachite is present on joints and bedding planes in quartz and feldspathic sandstone below the second basalt flow.

Type (iii) occurrences: The Number 9 show (16°44′50″S, 127°40′00″E) was considered by Planet to be the best prospect in the Durack Ranges area. Malachite, chalcocite, cuprite, chalcopyrite and bornite occur as veinlets and disseminations in and adjacent to where a strike fault (northeast trend) and a northwest-trending fault intersect. The host rocks are basalt, brecciated basalt, epidotized rocks and sandstone (interbed in flows in upper part of sequence). The best mineralization is present along the northwest fault, which dips steeply to the northeast. Five diamond drillholes were put down to depths of 115 m to 122 m to test the mineralization in this fault down dip. Four of the five holes intersected mineralization. Over a length of 271 m a grade of 0.6 per cent copper was indicated for a drilled width of 28.6 m. Anglo American drilled a diamond drillhole to 151 m to test for enrichment of stratiform mineralization in the basal flow adjacent to the fault, but with negative results. A tentative indicated resource estimate of 1.84 Mt at 0.51 per cent copper was given by Orr (1971).

Several shows are grouped at the Durack Range South locality (16°45′20″S, 127°38′00″E) which is in the uppermost basalt of the sequence. Malachite, chalcocite, bornite and chalcopyrite occur in sheared vesicular basalt, epidotized rock and banded or black chert. Some mineralization is controlled by intersecting faults of similar orientation to those at Number 9 show.

Most mineralization at the Number 1 Copper Prospect is in shears but particularly in a sub-vertical shear zone trending 330 degrees, which is mineralized over a 106 m length and 14 m width. Bornite, chalcocite, chalcopyrite, cuprite, malachite and quartz occur as disseminations and stringers in this zone. A channel sample over the 14 m width assayed 0.96 per cent copper and one over 5.5 m returned 2.45 per cent copper. Disseminated chalcocite and malachite are also present in quartz veins up to 200 m long and a few centimetres thick, which trend between 330 degrees and 020 degrees. Only two of these veins appear to be mineralized; a chip sample across the thicker one assayed 1.55 per cent copper over a 7.3 m width. This show seems to have some features in common with the Number 9 show and was regarded as next in importance to this show by Planet (1971).

Type (iv) occurrence: At the Number 14 show (17°05′00″S, 127°24′30″E) malachite, chalcopyrite, bornite and chalcocite are present in veins and disseminations in the top of the lowest basalt, which is amygdaloidal. Chalcocite veins are exposed in a creek bed over an area 4.6 m by 15.2 m. A (vertical?) diamond drillhole put down in 1969 and terminated at 52.3 m assayed 0.84 per cent copper from 23 cm at 35.6 m depth and 0.75 per cent copper from 1.52 m at 27.4 m depth. The rest of the hole assayed less than 0.26 per cent copper.

OTHER OCCURRENCES

These occurrences are described from north to south.

The Cape Bougainville occurrence (ca. 13°54′S, 126°06′E) is mentioned by both Simpson (1948, p. 424) and Harms (1959). Small blebs of chalcopyrite were found in epidotized basalt near the Cape by a survey party in 1924. At Drysdale River Estuary (13°57′30″S, 126°57′30″E), Gellatly and Sofoulis (1969) mention chalcopyrite amygdales up to 5 mm in size in basalts. A similar occurrence is at Saint George Basin (15°18′S, 125°09′E) mentioned by Williams and Sofoulis (1971). The location of the Augustus Island occurrence (15°30′S, 124°35′E) is not reliable but the report (Harms, 1959) possibly refers to cupriferous basalt exposed on the shoreline of the island. Doubt surrounds the position of the Brecknock Harbour occurrence because Harms (1959) reports a location (15°30′S, 124°40′E) which plots on the east side of Camden Peninsula, whereas Simpson (1948, p. 411) described weathered basic rock with malachite and chalcocite on the north shore of the inlet (presumably referring to Brecknock Harbour). There may be two distinct occurrences.

The Doubtful Bay occurrence is also problematical. Simpson (1948, p. 411) gives a location (16°05′S, 124°30′E) which plots in the sea, but which could refer to the east of Raft Point where Carson Volcanics occur. Harms (1959) gives a location (16°00′S, 124°30′E) which plots on the northern side of the bay in a headland of Warton Sandstone. The High Range West occurrence (16°29′20″S, 124°07′50″E) is shown on the Yampi Sheet a short distance above a feldspathic sandstone interbed in the Carson Volcanics. An occurrence of chalcopyrite and malachite disseminated and in vugs, near Barnett River Gorge (16°33′30″S, 126°06′30″E) is mentioned by Harms (1959) and Roberts and Perry (1970). The Narrie Range occurrence (17°30′00″S, 126°31′30″E) consists of disseminated chalcopyrite in basal flows (Gellatly and Derrick, 1967). Three occurrences (probably similar to Narrie Range) have been reported from the Mueller Range area (18°19′40″S, 126°54′00″E; 18°15′00″S, 127°00′20″E, 18°09′10″S, 127°05′30″E).

HART DOLERITE

GEOLOGY

The Hart Dolerite consists of a series of anastamosing dolerite-gabbro sills of tholeiitic affinities which intrude the Speewah Group and the Kimberley Group as high as the Middle Pentecost Sandstone, though commonly the sills do not intrude above the Carson Volcanics.

Dow and Gemuts (1969) suggested that much of the Hart Dolerite is coeval with the Carson Volcanics. Where in contact the two formations can be difficult to distinguish (Gellatly and Sofoulis, 1973, p.13; cf. Edwards, 1943). Hart Dolerite from the Landsdowne Sheet area has been dated at about 1 800 m.y. which is indistinguishable from determinations on the Carson Volcanics (Bofinger, 1967), but some dolerite pretrologically similar to the Hart Dolerite is evidently younger. When fresh the dolerite contains two pyroxenes, plagioclase, minor olivine, micropegmatite, quartz and accessory magnetite and apatite.

The formation is thickest and most extensive in outcrop around the southern perimeter of the Kimberley Basin. Here the thicker sills are differentiated and dark grey dolerites are capped by pink-grey granophyre; the formation attains maximum thicknesses in the range of 1 000 m to 3 000 m. Thin, but very persistent, northwesterly trending dykes on the Lennard River and Charnley Sheets may be feeders for some of the sills. The Hart Dolerite is probably less than a few hundred metres thick in the northern part of the basin, and is only widespread in the northwest, being absent in the extreme northeast (Medusa Banks Sheet).

MINERALIZATION

There are three types of mineralization present in the Hart Dolerite:

(i) disseminated chalcopyrite (with pyrite), bornite and malachite;

(ii) minor amounts of copper minerals in quartz veins; and

(iii) accessory or minor amounts of copper minerals associated with silver-lead or fluorite bearing quartz veins.

The first type is widespread and is recorded from the Prince Regent, Drysdale, Yampi, Mount Elizabeth, Lissadell and Landsdowne Sheets, but the second and third types have only been reported from isolated localities in the western and eastern outcrops of the formation respectively.

In general, mineralization of any kind appears to be sparse compared with the Carson Volcanics, although the poorer, more rubbly outcrop of the Hart Dolerite may have caused some adverse discrimination during field work in the past. None of these occurrences has been inspected by the author.

Type (i) occurrences: The occurrence at Wilson Point (15°33′S, 124°26′E) referred to by Williams and Sofoulis (1971) is assumed to be of this type. Disseminations and rare clots of chalcocite and chalcopyrite are present in loose boulders of Hart Dolerite intruding Pentecost Sandstone at Karunjie (16°17′40″S, 127°10′50″E). Most boulders in the rubbly outcrop are barren (Roberts and Perry, 1970). The co-ordinates of the Glenelg River occurrence (15°40′S, 124°48′E) given by Harms (1959) plot in outcrop of the King Leopold Sandstone, but as this is liberally intruded by dolerite in the general region, it is included here. At Moonlight Valley Yard (16°30′30″S, 128°02′30″E) Dow and Gemuts (1969, p. 103) reported malachite and azurite joint coatings in uralitized dolerite intruding Speewah Group rocks.

Type (ii) occurrences: At the Amphibolite prospect (16°31′50″S, 124°10′50″E) a north-northwest trending sericitized shear zone contains sporadic copper-iron mineralization in quartz pods and veins (Sofoulis, 1967). Three shallow prospecting pits reveal a mixture of malachite, bornite, cuprite and iron oxides.

The Mount Hart occurrence (16°55′S, 125°03′E) consists of quartz veins with copper carbonates in coarse-grained 'diorites' of the Hart Dolerite near a north-trending fault (Harms, 1959).

Type (iii) occurrences: The Shangri La mine (Costeo's) is 18 km west of Kununurra and immediately north of the Duncan Highway (15°46′40″S, 128°34′10″E). Though called a mine there is no recorded production from the deposit, which has been described by Sofoulis (1968) and Blockley (1971b, p. 113). Small amounts of chalcopyrite, bornite and tetrahedrite (and oxidized derivatives) accompany galena and sphalerite disseminations and bunches in gently north-dipping quartz veins emplaced in Hart Dolerite. Percussion drilling by Conwest in 1968 suggested reserves of 34 500 t averaging 7.6 per cent lead, 0.4 per cent copper, 302 g/t silver, and 56 g/t gold. Assays of copper were less than 0.85 per cent and of zinc less than 1.25 per cent. The gold and silver are associated with the copper rather than the lead minerals.

Martins (or Duracks) silver-lead prospect (16°13′00″S, 127°58′40″E) contains small quantities of azurite and malachite associated with galena and cerussite in a 1 m thick quartz vein which dips gently east (Blockley, 1971b, p. 117). The vein occurs in a soil covered area and is traceable for 250 m. In 1969 Planet (Apthorpe, 1971) drilled sixteen percussion drillholes at the prospect: patchy low grade mineralization was intersected. A similar quartz vein at the Calamondah prospect (16°14′30″S, 127°57′40″E) is 600 m long, 4 to 6 m thick and dips east at about 15 degrees. Secondary copper minerals are disseminated irregularly through the quartz at the surface at the northern end of the vein, but seven percussion drillholes put down by Planet showed that the mineralization dies out in depth.

During exploration in the Speewah Valley, Planet found several additional minor occurrences of copper and lead mineralization associated with northerly trending quartz veins in the dolerite.

Martins fluorite prospect (16°21′00″S, 127°57′10″E) occurs 11 km north of the ruins of Speewah homestead. Plumb (1968, p. 27) refers to azurite in a shear zone associated with epidote and quartz at this locality and also describes galena and fluorite apparently from the same place (Plumb 1968, p. 28). Blockley (1971b, p. 117) refers to the same locality as the 'Speewah Prospect' (this name has been dropped here to avoid confusion with Speewah prospect 4.6 km north-northeast of the homestead) and gives the same details as Plumb (1968, p. 28).

The Speewah fluorite prospect (16°25′00″S, 127°58′30″E), discovered by Great Boulder in 1972 (Schultz, 1972), occurs in a major north-northeast trending fault zone which branches from the Greenvale Fault further south. The fault zone cuts granophyre of the Hart Dolerite which has intruded and rafted sedimentary rocks of the Speewah Group. Quartz and fluorite veins fill shears in these rocks over a 6 km strike length, but the zone of intense mineralization appears to be about 2 km long. The main veins contain fluorite and quartz with barite in some cases. Stockworks and stringer veins adjacent to the main veins contain minor amounts of chalcopyrite in addition to these minerals. Copper grades in twenty-five diamond drillholes sunk by Great Boulder in 1973 range from 0.01 to 0.47 per cent and average about 0.1 per cent.

Gellatly and Derrick (1967, p. 24) reported chalcopyrite associated with galena in a quartz vein cutting Hart Dolerite at Coolan Creek Yard (17°47′20″S, 126°34′50″E).

OTHER OCCURRENCES

The Coppermine Creek deposit (16°13′30″S, 123°36′50″E) has also been called the Yampi Sound copper deposit, Water Point (Low, 1963). Chalcocite, malachite, cuprite, atacamite and brochantite occur in quartz veins up to 2 m thick which are emplaced in sheared, sericitized and carbonated quartz porphyry of the Wotjulum Porphyry (Sofoulis, 1967). The mineralization is exposed over a 9 m length and 0.6 m width and dips east. The deposit was mined in 1912-1915 and yielded 94.35 t of ore containing 23.17 t of copper. The Wotjulum Porphyry is extensive in the northwest Yampi Peninsula and intrudes the upper Warton Sandstone, the Elgee Siltstone and lower Pentecost Sandstone in areas where the Hart Dolerite is absent at these stratigraphic levels. Gellatly and Sofoulis (1973, p. 13) suggest that the porphyry is penecontemporaneous with the Hart Dolerite.

Dow and Gemuts (1967) noted several malachite-azurite shows from the Fish Hole Dolerite during mapping of the Dixon Range Sheet. Two occurrences are shown on this sheet at Fish Hole Waterhole (17°25′S, 128°11′E) and Osmond Range West (17°17′20″S, 128°14′10″E). The mineralization does not exceed 15 m by 0.5 m in outcrop area at either locality.

CHAPTER 5

Central and northern Australian platform cover

GEOLOGY

Included in this category are the Birrindudu, Victoria River and Amadeus Basins which contain rocks of middle to upper Proterozoic age plus some Palaeozoic rocks in the Amadeus Basin. The stratigraphy of these basins is summarized in Tables 12 and 13. Stratigraphic relationships in the parts of the Birrindudu and Victoria River Basins within the State are complex. The stratigraphic schemes proposed by Plumb and Derrick (1975) and Blake and Hodgson (1975) have been adopted here. The rocks in these two basins are confined to the East Kimberley region, with the exception of the Birrindudu and Redcliffe Pound Groups which are extensive south of 18 degrees south latitude in the area adjacent to the Northern Territory.

The Birrindudu Basin was mildly folded, faulted and eroded before development of the Victoria River Basin began about 1 150 m.y. ago. The Victoria River Basin is virtually undisturbed where most extensive in the Northern Territory, but a thick terrigeneous sequence with numerous unconformities and complex facies changes developed in the mobile zone coincident with the eastern arm of the Halls Creek Province. Uppermost Proterozoic glacial successions unconformably

TABLE 12. SUMMARY OF STRATIGRAPHY OF BIRRINDUDU AND VICTORIA RIVER BASINS IN WESTERN AUSTRALIA

Group	Formation	Remarks
Albert Edward Group	Flat Rock Formation	Dolomitic and ferruginous sandstone.
	Nyuless Sandstone Timperley Shale Boonall Dolomite	
	Elvire Formation Mount Forster Sandstone	Shale and siltstone.
	unconformity	
Duerdin Group	Ranford Formation	Siltstone, sandstone, shale.
	Moonlight Valley Tillite	Dolomitic at top.
	unconformity	
	Frank River Sandstone Fargo Tillite	
	unconformity	
	VICTORIA RIVER BASIN	
Carr Boyd Range Group	Bandicoot Range Beds	Stratigraphic position unknown.
	Pincombe Formation Stonewall Sandstone	Siltstone and sandstone.
	unconformity	
	Glenhill Formation	Glauconitic sandstone interbeds
	unconformity	
	Lissadell Formation	Minor tuff and pyritic siltstone.
	unconformity	
	Golden Gate Siltstone Hensman Sandstone	Pyritic in places, tuffaceous in southwest.
"Osmond Range Succession" 1	Helicopter Siltstone	Equivalent to Golden Gate Siltstone
	Wade Creek Sandstone	
	Mount John Shale	Some black shale
	unconformity	
	BIRRINDUDU BASIN	
Redcliff Pound Group 2	Erica Sandstone Kearney Beds	Present on Billiluna, Lucas and Stansmore Sheets
	unconformity	
Birrindudu Group	Gardiner Sandstone 3 Talbot Well Formation Coomarie Sandstone	Probably equivalent to Bungle Bungle Dolomite and Mount Parker Sandstone
"Osmond Range Succession"	Bungle Bungle Dolomite	Stromatolitic, isolated Cu occurrence.
	Mount Parker Sandstone	
	Colombo Sandstone	Restricted to Louisa Downs area, probably equivalent to Mount Parker Sandstone.
	unconformity	
	RED ROCK BEDS	

1. Informal name applied by Thom (1975, p. 176).
2. Placed in this position by Blake and Hodgson (1975) but regarded as part of Victoria River Basin by Plumb and Derrick (1975).
3. Age of sedimentation and diagenesis probably about 1 560 m.y. (Page and others, 1976).

TABLE 13. SUMMARY OF STRATIGRAPHY OF AMADEUS BASIN IN WESTERN AUSTRALIA

Age	Formation	Remarks
Siluro-Devonian (?)	Marcenie Sandstone	
Ordovician	Limestones and sandstone	
Upper Proterozoic	Maurice Formation	Arenaceous
	unconformity	
	Ellis Sandstone and Sir Frederick Conglomerate	
	Bord Formation and Carnegie Formation	(Glacial)
	unconformity	
	Bitter Springs Formation	Dolomite, chert, gypsiferous siltstone; stromatolitic.
	Heavitree Quartzite	

overlie these and older rocks and are in turn mildly deformed and faulted where in or adjacent to the mobile zone.

The bulk of the Amadeus Basin in the State comprises Proterozoic sedimentary rocks of mixed terrigeneous and calcareous types. The basin is mildly folded and faulted.

MINERALIZATION

The only recorded mineralization in the whole area is at Osmond Range (17°08'S, 128°31'E) from the lower part of the Bungle Bungle Dolomite (Birrindudu Basin) which dips gently to the north-northeast here. This occurrence is shown on the Dixon Range Sheet (Dow and Gemuts, 1967) but is not mentioned in the text of the explanatory notes. This formation contains abundant stromatolites at some horizons and seems to represent a widespread marine transgression following the deposition of the Mount Parker Sandstone. Plumb and Derrick (1975, p. 246) note that an easterly thinning of sandstone beds in the Bungle Bungle Dolomite is suggestive of a westerly provenance from the eastern arm of the Halls Creek Province. The setting of this formation therefore appears favourable for stratiform copper mineralization, because such mineralization is commonly associated with very shallow water marine sequences transgressive over terrigenous arenite beds adjacent to a cupriferous basement area. By analogy with the African copperbelt the basal arenites of the Mount Parker Sandstone also merit attention. The basement area in this case includes the lower Proterozoic crystalline rocks of the Halls Creek Province which contain scattered copper mineralization, and the stratabound copper-bearing formations of the Kimberley Basin. Besides the Osmond Range (Dixon Range Sheet) the Bungle Bungle Dolomite and Mount Parker Sandstone crop out in the Albert Edward Range (Gordon Downs Sheet). Simpson (1951, p. 127) reported specimens containing cuprite, malachite and limonite from the Elvire River which drains this area but the source could be the Cambrian basalts of the Antrim Plateau Volcanics which occur east of the river.

The pyritic or tuffaceous parts or facies of the Golden Gate Siltstone and the Lissadell Formation (both part of the Carr Boyd Range Group of the Victoria River Basin) may be worthy of some attention in a regional prospecting programme for stratabound copper mineralization.

The remoteness of the Amadeus Basin must relegate it well down in any list of potential base metal mineralized terrains of exploration interest. However the stromatolitic carbonate-evaporite sequence of the Bitter Springs Formation offers some inducement as a stratabound copper target if adequate metal sources and sulphate-reducing agents were available at the appropriate time and place in the depositional and diagenetic history of the formation.

CHAPTER 6

Halls Creek Province

SUMMARY AND CONCLUSIONS

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). The stratigraphic nomenclature applied to many of the rock groups in the province lacks uniformity and rationality; a broad summary is given in Table 14. There is little merit in retaining the sack term 'Lamboo Complex' because it has been used (e.g. Gellatly and others, 1968; Thom, 1975) to encompass all rocks except the Halls Creek Group, although the Whitewater Volcanics were included. An arbitrary division was made on the basis of metamorphic grade, between low to medium-grade and medium to high-grade metamorphic rocks of the older supracrustal assemblage, into the Halls Creek Group and the Tickalara Metamorphics respectively. There are large areas of both medium-grade Halls Creek Group and Tickalara Metamorphics (Gemuts, 1971, Fig. 6), so the scheme is only workable in restricted areas at opposite ends of the metamorphic spectrum. In some areas separate granitoid intrusions are lumped into one large batholith (e.g. the Bow River Granite, one of the younger granitoid suite, is 300 km long and 30 km wide), whereas elsewhere many smaller intrusions are recognized (e.g. Lennard River Sheet).

In the central parts of the Halls Creek mobile zone (Dixon Range, Gordon Downs, Lansdowne and Mount Ramsay Sheets) the Halls Creek Group has been subdivided into four formations, although only the upper two are widespread (Table 15). The bulk of the undivided rocks of the group in the West Kimberley region was regarded as possibly correlative with the Olympio Formation, probably because of a general lack of recognized metavolcanic and carbonate rocks. The monotonous psammitic to semi-pelitic quartz-mica-chlorite schists and phyllites of the West Kimberley and part

TABLE 14. SUMMARY OF GROSS STRATIGRAPHY AND CUPRIFEROUS MINERALIZATION OF THE HALLS CREEK PROVINCE

Informal group	Lithology and formal names	Age relationships and radiometric data*	Cupriferous mineralization
Younger granitoid suite	Various aphyric and porphyritic biotite and/or hornblende granite, adamellite and granodiorite units;	Intrudes Whitewater Volcanics and older rocks, unconformably overlain by Speewah Group; 1 850-1 880 m.y.	Cupriferous quartz veins.
Younger supracrustal assemblage	Rhyodacitic ignimbrites, tuffs, agglomerates and tuffaceous sedimentary rocks (Whitewater Volcanics); some coeval hypabyssal porphyries.	Unconformable on older supracrustals; ca. 1 950 m.y. (?)	Rare cupriferous quartz veins.
		unconformity	
Older granitoid suite	Various aphyric and porphyritic biotite and/or hornblende granitoids ranging from granite to diorite in composition; commonly foliated and xenolithic, may be anatectic in part.	Intrudes older supracrustals, some may be metamorphosed; ca. 1 960 m.y. (metamorphic age?).	Cupriferous quartz veins.
Older supracrustal assemblage	(a) Variably metamorphosed mafic to ultramafic intrusives, some thick differentiated sills; Wombarella Quartz Gabbro, McIntosh Gabbro, Woodward Dolerite, Alice Downs Ultrabasics.	Mostly penecontemporaneous with other older supracrustals, but some are post—or late—metamorphism.	1. *Massive and disseminated* iron-copper-nickel sulphides in gabbroids. 2. Cupriferous quartz veins.
	(b) Variably metamorphosed arenaceous, argillaceous and carbonate sedimentary rocks and felsic or mafic volcanic rocks; gneisses and granulites; Halls Creek Group and Tickalara Metamorphics.	Relationships between the various high-grade metamorphic and gneissic rocks not properly established, 2 050-2 100 m.y. (?)	1. Polymetallic massive and disseminated sulphides in felsic metavolcanics, carbonaceous phyllites and carbonate rocks. 2. Cupriferous quartz veins and shears. 3. Disseminated copper mineralization.
Basement rocks (?)	Various gneisses, Tickalara Metamorphics in part (?)	Archaean (?)	

*Preferred radiometric ages from Page (1976) of the Olympio Formation in the East Kimberley are lithologically similar to the Mosquito Creek Formation (Archaean) of the East Pilbara. However as discussed by Page (1976) there is no adequate evidence to substantiate the widely held belief that the Halls Creek Group may be Archaean in depositional age. It is conceivable that some of the complex gneissic rocks assigned to the Tickalara Metamorphic are reworked Archaean rocks.

Cupriferous quartz veins and shears are ubiquitous but more important mineralization is restricted to the older supracrustal assemblage, particularly stratabound polymetallic deposits in the Halls Creek Group (Table 15) and disseminated or massive copper-nickel deposits in gabbroid complexes intruding the Tickalara Metamorphics (Plate 2).

There are two major types of polymetallic mineralization both of which are metamorphosed and deformed along with their host rocks. The mean copper-zinc ratio of five deposits is 0.36 with a standard deviation of 0.18. Firstly, massive and disseminated iron-copper sulphides plus subordinate zinc-lead sulphides (which if not an integral part of the cupriferous mineralized zone are closely associated with it spatially), occur in mixed sequences of quartz-muscovite-chlorite phyllite, quartz-eye sericite schist and other felsic metavolcanic rocks. Examples are the Eastmans Bore, Golf Course, Koongie Park Southwest and Mount Angelo prospects. Impersistent banded iron formation and chert may be associated with the mineralized horizon which is folded and lineated along with the country rocks. Massive sulphide mineralization seems to occur in small pods which may have complex shapes in three dimensions (partly because of tectonism), and tend to have very variable metal grades. Bulk copper grades of primary ore are generally probably less than 2.5 per cent.

Secondly, disseminated and subordinate massive sulphides of iron, copper, zinc, lead, antimony and arsenic are found in less varied sequences of carbonaceous quartz-mica-chlorite phyllite commonly accompanied by minor amounts of felsic schist probably partly volcanic in origin. The best examples come from the West Kimberley region (e.g. Chianti and Turtle Creek prospects). The mineralized zones are generally shorter and thinner and more disseminated in character than is the case for the first mineralization type. Individual copper grades are lower, being less than 2 per cent in general. The Little Mount Isa and Ilmars prospects are essentially zinc-rich variants of this second type, in metasedimentary sequences containing a major component of layered carbonate rocks. The primary sulphides from both prospects average less than 0.3 per cent copper.

The best prospects for finding massive sulphides of bulk grade 2 per cent copper or above would appear to rest with stratabound polymetallic mineralization of the first type. The present shape and internal structure of ore bodies is likely to be complex because of metamorphism and deformation. The original ores were probably of volcanogenic origin.

Iron-copper-nickel sulphides are present in partially metamorphosed gabbro-norite-troctolite complexes, which in two places (Bow River and Sally Malay prospects) are clearly younger than surrounding high-grade gneisses of the Tickalara Metamorphics. Massive mineralization may partly result from the concentration of disseminated sulphides during later tectonism and metamorphism (e.g. Corkwood, Bow River and Sally Malay prospects). It is feasible that a gabbroid suite intruded after the main tectono-thermal events responsible for the generation of the Tickalara Metamorphics is mineralized in preference to mafic suites intruded at an earlier stage into the older supracrustal assemblage. The prospects for further discoveries appear bright although examples of mineralization found so far are either small, moderate grade (i.e. about 3 per cent combined nickel and copper) massive sulphides lenses (e.g. Sally Malay, Corkwood) or large disseminated sulphide bodies of insufficient grade to be of economic interest (Bow River).

TABLE 15. STRATIGRAPHY AND COPPER MINERALIZATION OF THE HALLS CREEK GROUP

Formation	Lithology	Mineralization and remarks
Olympio Formation	Metamorphosed subgreywacke, arkose and conglomerate; phyllite, minor quartzite, carbonates, black slate, chert and felsic metavolcanics.	1. Massive and disseminated Cu-Zn sulphides in felsic metavolcanic rocks. 2. Disseminated copper in metasedimentary rocks. 3. Cupriferous quartz veins
Biscay Formation	Metamorphosed mafic volcanics and subordinate felsic volcanics intercalated with greywacke, siltstone, slate, carbonaceous slate chert and carbonate rocks.	1. Stratabound massive Zn-Pb-Cu sulphides in semipelitic and carbonate schists. 2. Disseminated copper in mafic metavolcanics. 3. Disseminated copper in hypabyssal and extrusive felsic igneous rocks. 4. Cupriferous quartz veins.
Saunders Creek Formation	Metamorphosed quartzose and feldspathic sandstone and greywacke; slate and conglomerate at base.	Restricted to Gordon Downs and Mount Ramsay Sheets.
Ding Dong Downs Volcanics	Mafic metavolcanics, minor felsic metavolcanics, quartz-mica-schists and slate.	Restricted to Gordon Downs and Mount Ramsay Sheets; 1. Disseminated copper in amygdaloidal metabasalt. 2. Cupriferous quartz veins.
Undifferentiated Halls Creek Group	Quartz, muscovite, sericite, chlorite schists, locally chloritoid, andalusite, staurolite, kyanite or garnet bearing; phyllite, slate, metamorphosed greywacke, rhyolite and carbonate rocks.	1. Cupriferous quartz veins. 2. Polymetallic stratabound mineralization.

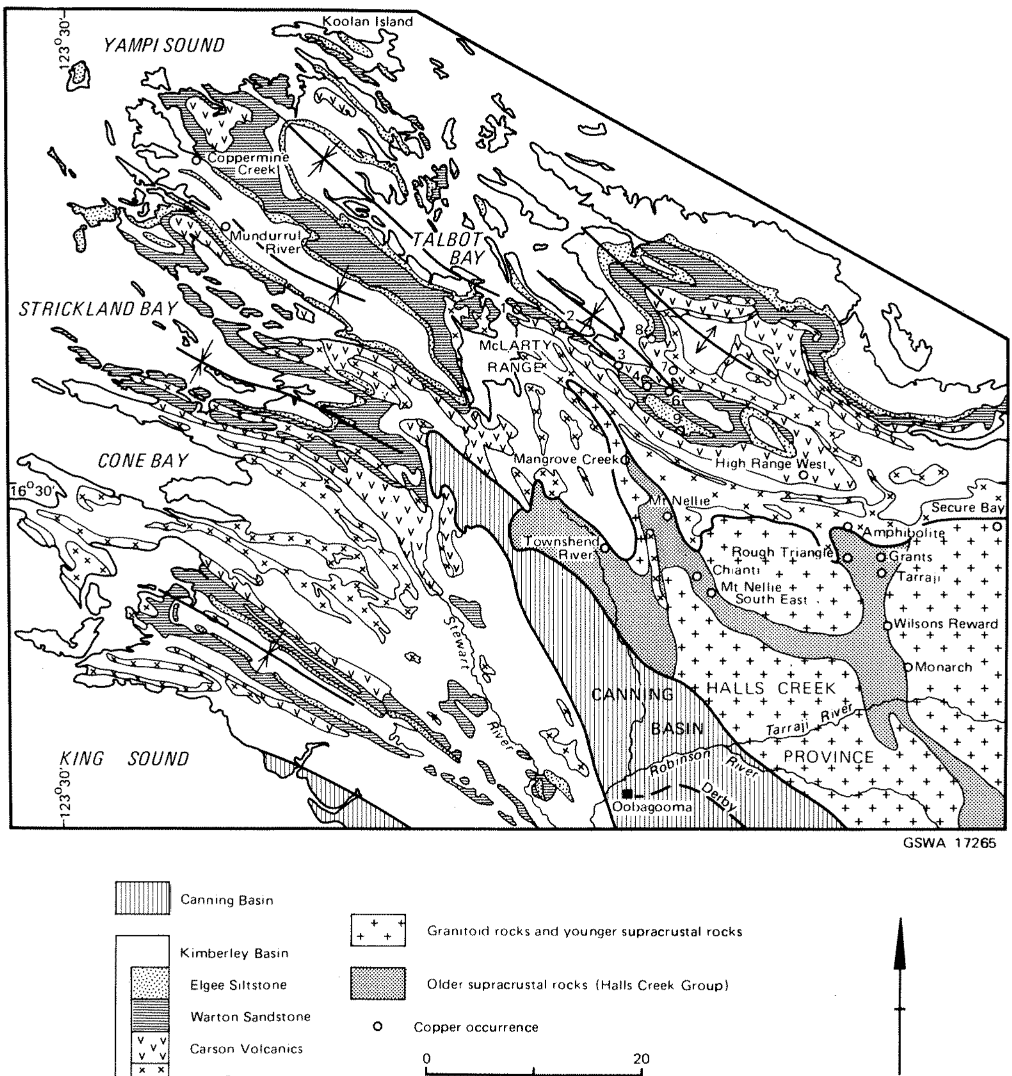

Figure 6. Copper occurrences in the Yampi Peninsula

Cupriferous quartz veins and shears occur in all rock types in the Halls Creek Province but are commonest in Halls Creek Group rocks and rocks of the younger granitoid suite. It is unlikely that any of these occurrences is of economic significance in its own right, but some importance may attach to veins in supracrustal rocks as possible indicators of stratabound mineralization nearby. Cupriferous veins are particularly common in the extreme West Kimberley region in monotonous quartz-muscovite phyllites (Fig. 6). However the mineralization is weak and impersistent and the stratabound mineralization already found in such rocks (type 2 above) is low grade and small in amount.

The one example (Mount Angelo South) of disseminated iron-copper sulphides in hypabyssal-extrusive porphyritic felsic igneous rocks seems to be of insufficient grade and size to be of economic interest. The mineralization is apparently not of the porphyry copper type.

STRATABOUND POLYMETALLIC MINERALIZATION IN HALLS CREEK GROUP ROCKS (TYPE A)

DEPOSITS IN METAMORPHOSED FELSIC VOLCANO-SEDIMENTARY SEQUENCES

All these deposits have been inspected by the writer.

GOLF COURSE PROSPECT

The Golf Course prospect (18°12′40″S, 127°39′30″E) is 2 km north-northwest of Halls Creek in medium-grade metamorphic rocks shown as Biscay Formation on the Gordon Downs Sheet, near the eastern edge of a complex granitoid mass (Bow River Granite). Discontinuous malachite-stained limonitic gossans up to 4 m thick with a strike extent of 150 m, occur in an east-northeast striking, complex sequence of lineated quartz-eye, sericite chlorite schists and statically recrystallized metabasalt and metadolerite. In parts the sequence is strongly hornfelsed and partly mobilized; crosscutting mafic intrusives further complicate the geology. The main gossan is only 60 m long and dips steeply to the south-southeast apparently concordant with the host rocks. A calc-silicate-magnetite horizon 1 to 2 m thick occurs along strike at the western end of the gossan. Banded iron formation (BIF) and semi-pelitic phyllite occur to the east, structurally overlying the quartz-eye schists which themselves may be deformed felsic pyroclastics. A small zinc-lead gossan occurs at the structural base of the phyllite sequence in a pyritic cherty rock. The copper gossan was found by Peko in 1963 who sank a diamond drillhole under the southern part of the gossan, but the hole did not intersect significant mineralization. PMI carried out surface exploration in 1970-1971, followed by Kennco who put three shallow costeans across the copper gossan.

KOONGIE PARK SOUTHWEST PROSPECT

The Koongie Park Southwest prospect (18°21′50″S, 127°29′00″E) is immediately northwest of the Great Northern Highway, 6.5 km southwest of Koongie Park homestead, in rocks assigned to the Olympio Formation (Roberts and others, 1968). Mineralization occurs associated with an isolated north-trending, small rugged ridge, and is expressed as variably silicified gossans cropping out discontinuously over 400 m southwards from the southern end of the ridge. Visible copper mineralization was not seen but I. Gemuts (pers. comm., 1976) states that malachite was recorded during regional mapping by joint Bureau of Mineral Resources and Geological Survey of Western Australia parties. The gossans are located at or near a contact between (a) fine-grained white to purple, micaceous, chloritic phyllite containing quartz-eye textured horizons and massive chert lenses to the west, and (b) white to maroon weathering (probably chloritic) quartz-eye schists, which may be metamorphosed crystal tuffs, to the east. Sulphidic BIF and chert intergrade and may be a facies equivalent of the mineralized zone. Oxidized metamorphosed spherulitic felsic lavas occur west of the phyllites. Foliation and layering strike north and dip steeply east. A steeply south-southeast plunging mineral lineation in the BIF's appears coaxial with mesoscopic sinistral drag folds. Since 1972 Kennco have carried out intensive exploration at this occurrence including a substantial diamond drilling programme. Massive and disseminated iron-copper-zinc and minor lead sulphides have been intersected.

MOUNT ANGELO PROSPECT

The Mount Angelo prospect (18°26′30″S, 127°29′20″E) also known as 'Angelo North' and 'Peko Angelo', is 6.8 km at 101 degrees from Mount Angelo hill (adjacent highway). It occurs in north-northeast striking, low-grade metamorphic rocks ascribed to the Biscay Formation (Dow and Gemuts, 1969, p. 100) preserved east of the northeast-trending Mount Angelo Fault and west of a sub-parallel splay fault. Two prominent, clinkery limonitic copper gossans occur 150 m apart and measure 60 by 18 m and 60 by 12 m in outcrop. Disseminated malachite, azurite and cuprite plus carbonate are visible in very shallow pits on the east side of the larger gossan. The immediate host rocks are moderately east dipping, pale maroon weathering, fine-grained quartz-mica-chlorite phyllites, including very thin BIF horizons and massive or weakly banded chert. Some felsic units with lensoid foliation (sub-parallel to layering) and a pyroclastic or extrusive aspect occur in the host sequence also. The host sequence as a whole is at or near the western contact of a distinctive pale grey-green spherulitic meta-rhyodacite with foliated, pale cream felsic tuffs. The overall sequence appears comparable from limited field observations, with that described at the Koongie Park Southwest occurrence. In 1962 to 1963 Peko investigated the prospect, intersected massive sulphides in drill core and inferred reserves of 203 000 t of primary ore (2.3 per cent copper) 203 000 t of secondary ore (2-4 per cent copper) and 102 000 t of pyritic ore (0.5 per cent copper), as quoted by McNeil (1966). In 1966 PMI drilled geophysical targets below the northern gossan and encountered pyritic sulphides with only minor amounts of chalcopyrite: the mineralization was thought to be concentrated in fold closures. Subsequent exploration has failed to find further encouragement.

EASTMANS BORE PROSPECT

The Eastmans Bore prospect (18°42′30″, 126°32′30″) is 3.4 km at 292 degrees from Eastmans Bore, in a west-southwest striking, steeply dipping sequence of poorly exposed quartz—or feldspar—phyric metarhyolite, felsic metavolcanic breccia, quartz-sericite schists, quartz-mica-chlorite phyllite, calc-silicate schists and metagabbro or metadolerite. Minor folds and mineral lineations plunge at moderate angles to the west. A low jagged outcrop of sheared rhyolite and rhyolitic breccia some 60 m long contains narrow zone of malachite-chrysocolla disseminations. In common with the Golf Course prospect zinc-lead mineralization is associated with the copper, specifically in talcose carbonates (sedimentary origin?). Diamond drilling in the area by Newmont and Kennco in 1969-1972 encountered disseminated zinc, copper and lead sulphides over very short strike lengths and widths of several tens of metres, but at individual metal grades commonly less than 2 per cent.

DEPOSITS IN METASEDIMENTARY SEQUENCES

CHIANTI PROSPECT

The Chianti prospect (16°34′20″S, 124°03′00″E) is 23 km north-northeast of Oobagooma homestead, by which access can be gained. Small copper gossans occur discontinuously in a zone 150 m long within a sequence of north-striking slates and quartz-sericite schists (undifferentiated Halls Creek Group) intruded and broken up by metadolerite and situated just north of the Lennard Granite. Three diamond drillholes put down by ACM in 1972 (Jessup and Yeaman, 1972) intersected dominantly iron sulphides, with minor chalcopyrite, sphalerite and galena, in graphitic slates. One hole cut massive ore accompanied by breccia ore, which may have been mobilized and upgraded (?) into a small pod within metadolerite. The best intersection in this hole (DDH3) was 6.63 m of 1.06 per cent copper, 0.93 per cent lead, 2.85 per cent zinc and 29 g/t silver.

TURTLE CREEK PROSPECT

The Turtle Creek prospect (17°25′00″S, 125°18′40″E) is shown on the Lennard River Sheet as being in steeply dipping undifferentiated Halls Creek Group rocks intruded by a series of deformed and metamorphosed porphyritic dolerite sills (Woodward Dolerite). Three mineral prospects (Top Springs, Turtle Creek and Colemans Creek), to which there is no easy access at present, are sited on the northeast limb of a northwest-trending antiform in sheared metadolerite (Top Springs) or carbonaceous phyllites spatially associated with metadolerite (Turtle Creek and Colemans Creek). These occurrences were evaluated by WMC and Richenda in 1973-1974 (McConnell, 1973). The association with dolerite appears to be incidental. The copper gossan at Turtle Creek strikes northwest and is 270 m long (discontinuous) and generally less than 6 m wide, being truncated at each end by east-trending faults. The host rocks are laminated grey carbonaceous phyllites containing subordinate fine-grained felsites with flattened spherulites (felsic lavas?) and quartz-feldspar-mica-chlorite schists with a streaky foliation (?felsic tuffs). This host sequence is very similar to that at the Whim Creek copper-zinc deposit in the West Pilbara region. The phyllites are pyritic within 10 to 20 m of the mineralized zone. Shallow percussion drilling delineated a 100 m long zone carrying lead and silver values up to 6.5 per cent and 347 g/t respectively, but copper values were less than 1 per cent, except for a 15 m long area of limonitic gossan. Diamond drillhole RDH1 was sunk into the eastern end of this 15 m long area but only intersected disseminated pyrrhotite and chalcopyrite between 77 and 93 m. Fifty metres to the southeast diamond drillhole RDH2 intersected massive sulphides over a true width of 2.38 m which assayed 2.1 per cent copper, 3.5 per cent lead, 4.2 per cent zinc and 162 g/t silver. A further drillhole (RDH3) intersected the mineralized zone 45 m southeast of RDH2 and encountered 0.71 m true width of dominantly lead and zinc sulphides and sulphosalts. The massive sulphides are fine grained (less than 1 mm) except for rare aggregates of chalcopyrite and pyrite grains 1 to 2 mm in size, and are foliated parallel to the host rocks but are not laminated (see Appendix 1). McConnell (1973) recorded the following mineralogy for massive sulphides: pyrite, pyrrhotite, chalcopyrite, sphalerite (iron-bearing), bournonite ($PbCuSbS_3$), galena, tetrahedrite-tennantite, jamesonite ($Pb_4FeSb_6S_{14}$), tetradymite (Bi_2Te_2S), arsenopyrite, boulangerite ($Pb_5Sb_4S_{11}$), jordanite ($Pb_{14}As_7S_{24}$) and stibnite (Sb_2S_3).

COLEMANS CREEK PROSPECT

Colemans Creek prospect (17°29′00″S, 125°21′40″E) is 9.5 km along strike to the southeast of Turtle Creek prospect. The mineralized zone parallels layering and schistosity and dips very steeply to the northeast in chlorite-biotite-quartz phyllite containing metagreywacke and tuffaceous units. The zone comprises 1 to 3 cm thick gossanous lenses, cupriferous quartz veins and lenses and small areas of malachite staining extending over 75 m of strike. Two percussion drillholes put down to test induced polarization anomalies intersected minor disseminated pyrite and pyrrhotite mineralization with very low copper, lead and zinc assays.

TOP SPRINGS PROSPECT

The Top Springs prospect (17°23′50″S, 125°17′10″E) occurs 3 km northwest of the Turtle Creek prospect and consists of a 30 by 10 m gossan containing malachite and azurite in strongly sheared metadolerite. A grab sample from the gossan assayed 0.51 per cent copper, 0.9 per cent lead, 0.1 per cent zinc, 2.35 per cent arsenic and 6 ppm silver (McConnell, 1973). One percussion drillhole sunk by Richenda intersected 1.67 per cent copper between 12.2 and 15.2 m, but four percussion holes drilled by WMC only intersected iron sulphides in metadolerite and carbonaceous phyllite.

OTHER OCCURRENCES

Dow and Gemuts (1969, p. 101) reported copper shows (approx. 18°03′S, 127°58′E) in slates of the Biscay Formation north of the Saunders Creek uranium prospects. Peko drilled a self-potential anomaly in the area in 1962 but only found disseminated pyrite. Dow and Gemuts (1969, p. 102) also describe the discovery of copper minerals in 'sediment' (Olympio Formation) at Koongie Park (ca. 18°21′S, 127°32′E) during well sinking 1.2 km south of Koongie Park homestead. At Hangmans Creek Bore occurrence (18°42′00″S, 127°13′20″E) Dow and Gemuts (1969, p. 102) mention disseminated copper minerals in metagreywacke of the Olympio Formation.

ZINC-RICH DEPOSITS IN SEMI-PELITIC AND CARBONATE SCHISTS

Two deposits fall into this category: the Little Mount Isa (18°05′20″S, 127°50′40″E) and Ilmars (18°04′00″S, 127°51′40″E) prospects situated respectively 25 and 27 km northeast of Halls Creek in north-northeast striking and steeply west dipping rocks of the Biscay Formation, east of the Halls Creek Fault. Since their discovery in 1962 the deposits have been described by Gemuts (1963), Dow and others (1964), Dow and Gemuts (1969), Blockley (1971b) and Herbert (1971), and investigated by Peko, PMI and Kennco. At Little Mount Isa, a laminated siliceous pseudogossan averaging 10 m in thickness crops out as two parallel zones over nearly 500 m of strike in the summit of a hogsback ridge, and is sporadically stained with green secondary copper minerals. The host sequence comprises interlayered and intergradational carbonate-tremolite schists, carbonaceous slates, chlorite-biotite-carbonate-quartz schists and cherts. Peko drilled five diamond drillholes within the period 1963 to 1966, with discouraging results. Two diamond drillholes were sunk at the northern end of the gossan by PMI in 1969 to 1970 which intersected disseminated mineralization averaging 1 to 2 per cent zinc, 0.1 per cent copper and 0.1 per cent lead over drilled widths from 3 to 16 m. These holes were sited assuming that the ore body had a shallow northerly plunge. In 1975 Kennco drilled a deep hole which intersected the mineralized zone near the midpoint of its strike, and encountered thin layers and disseminations of pyrite, pyrrhotite, chalcopyrite, sphalerite and galena over 36 m. The average assay over this width was 8 840 ppm zinc, 1 169 ppm copper and 601 ppm lead. The highest copper assay within this width was 0.34 per cent over 1 m.

Herbert (1971) shows the Ilmars prospect to be at the northern end of a unit of mineralized quartz-muscovite-chlorite bearing schists which contain stratabound shows of copper carbonates over a 5 km strike length. He does not regard this unit as a correlative of the mineralized unit at Little Mount Isa. At the main prospect there are two mineralized zones. A southwestern zone 350 m long and up to 20 m wide of disseminated mineralization consists of malachite seams, veinlets and pods and cupriferous quartz veins in an intimately mixed carbonate-chlorite-chert-tremolite-limonite bearing layered sequence, enclosed in turn by foliated carbonate rocks with chlorite and talc foliae. Quartz-mica-chlorite schists dipping steeply west (concordant with the mineralized zone) and with a gently south-plunging mineral lineation, occur west of the enclosing carbonate rocks. A northeastern mineralized zone is about 200 m long and includes a 1 to 2 m thick gossan after massive sulphides with sporadic malachite, chrysocolla and cuprite. The gossan thickens where gently north-plunging flexural folds (axial planes inclined gently westwards) affect the sequence. The immediate wall rocks are carbonaceous phyllite and felsic schists possibly derived from ash tuffs. These rocks are in turn enclosed by finely laminated, fine-grained quartz-muscovite chlorite-biotite schists (metasiltstones?) with carbonate, cherty and amphibolitic horizons.

Seventeen diamond drillholes and five percussion drillholes were put into the Ilmars prospect by PMI. Despite the abundant copper showing in the gossans the sulphides bulk about 80 per cent pyrrhotite and pyrite, 16 per cent sphalerite, 3 per cent chalcopyrite and 1 per cent galena (Herbert, 1971). Arsenopyrite, tetrahedrite, tennantite, ilmenite and magnetite are accessory minerals. The best copper intersection was 1 per cent over 2.1 m. All other intersections contained less than 0.3 per cent copper. The ore tends to be copper rich at the base and zinc-lead rich at the top (west). The textures of the sulphides and associated silicates clearly show that the sulphides have been metamorphosed and deformed along with their host rocks. Sulphur isotope work by Herbert (1971) shows a small range in δS^{34} values with a mean (+ 0.03 per mil) very close to meteoritic sulphur indicating a magmatic source for the sulphur. Herbert (1971) concluded that syngenetic iron sulphide of fumarolic origin was desulphurised by metalliferous alkali halide brines of volcanic origin thereby resulting in base metal sulphide precipitation. In the absence of any evidence for dual sources it seems illogical to discount the simultaneous introduction of magmatic sulphur and metals into the basin.

STRATABOUND COPPER MINERALIZATION IN MAFIC IGNEOUS ROCKS (TYPES B AND C)

Dow and Gemuts (1969, p. 103) recorded copper carbonate staining in metadolerite (McIntosh Gabbro) at Fourteen Mile Bore (17°40′40″S, 127°58′10″E) a locality referred to as 'Douglas Well' by Harms (1959).

At the Bulman Waterhole occurrence (18°06′00″S, 127°58′30″E), native copper occurs in quartz and calcite amygdales in epidotized metabasalt of the Ding Dong Downs Volcanics near the contact with the Saunders Creek Formation (Gemuts and Smith, 1968). Mineralization is also present as disseminated pyrite and magnetite surrounded by a halo of magnetite in an area 61 by 3 m in size. Some very thin quartz veins also contain native copper. A non-amygdaloidal sample of metabasalt assayed 0.07 per cent copper (Dow and others, 1974).

Minor amounts of disseminated chalcopyrite in a dolerite dyke (probably within the Bow River Granite) were recorded by Dow and Gemuts (1969, p. 103) from Mount Amherst East (18°22′00″S, 127°02′50″E).

A metamorphosed layered ultrabasic-gabbroic-anorthositic intrusion west of Louisa Downs homestead and northeast of Eastman's Bore (centred at about 18°42′30″S, 126°36′00″E) contains minor disseminated pyrite and chalcopyrite in gabbro, and secondary copper minerals in shear zones within ultrabasic rocks. The intrusion strikes northeast for 10 km, dips steeply to the southeast and is up to 2 km wide in outcrop. The intrusion occurs along the northern margin of a porphyritic granitoid assigned to the Bow River Granite, and is cut by northeast and east-southeast trending faults.

At the Emull Bore prospect (18°26′10″S, 127°17′10″E), 7.2 km at 293 degrees from New Lamboo homestead, veinlets, aggregates and stains of malachite and chrysocolla occur with limonite in silicified, serpentinized, cumulate-textured peridotite and metagabbro. Locally the gabbro is leucocratic and may grade into iron-rich granophyre. The areas with visible copper mineralization are commonly less than 1 m square in outcrop area, and occur in a poorly exposed east-striking zone 500 m long and 150 m wide. Preliminary drilling by PMI intersected dominantly disseminated iron sulphides both in gabbro and serpentinite, but minor amounts of zinc, copper and lead sulphides appear to be more abundant in the ultramafic rocks near gabbro contacts. The best intersection was 1.6 per cent zinc, 0.9 per cent lead and 0.63 per cent copper from 30 to 45 m drilled depth (mainly below oxidized zone).

CUPRIFEROUS QUARTZ VEINS AND SHEARS (TYPE C)

HALLS CREEK GROUP AND TICKALARA METAMORPHICS

WEST KIMBERLEY REGION

A group of copper occurrences in undivided Halls Creek Group rocks in the West Kimberley has been described by Harms (1959) and Sofoulis (1967) and evaluated by WMC in 1957-1960 and PMI in the late 1960's. The occurrences are at Mangrove Creek, Townshend River, Rough Triangle, Grants Find, Tarraji, Mount Nellie Southeast, Wilsons Reward, Monarch and Mondooma and are described in that order, which is from north to south. Grants Find, Wilsons Reward and Monarch have been inspected by the writer. Access on the ground is difficult and slow, as old tracks are washed out and grown over.

The Mangrove Creek occurrence (16°29′00″S, 123°59′30″E) consists of iron-copper sulphides in slates near a contact with a metadolerite sill. Malachite (with vein quartz) disseminated on fracture and schistosity surfaces in mica-schists and phyllites has been noted from three localities at Townshend River (1. 16°32′50″S, 123°57′20″E; 2. 16°32′55″E, 123°57′30″E; 3. 16°33′20″S, 123°58′20″E). The mineralized area at one of these localities measured 150 m by 1 m in outcrop. The style of mineralization is similar at Rough Triangle prospect (16°33′30″S, 124°10′50″E) where a north-trending and steeply east-dipping silicified shear averaging 1.2 m in width, is traceable for 1 280 m in bleached and silicified phyllite. The mineralization appears restricted to a 200 m strike length at the northern end of the shear and the best showings occur where there is a little vein quartz.

The Grants Find (Grants Prospect, Grants Reward, Mount Nellie) mine (16°33′40″S, 124°12′30″E), is 19.4 km at 002 degrees from Boulder Hill. A hogsback ridge about 25 m above plain level is formed by a silicified and vein quartz-filled shear zone 1 km long and 1 to 3 m wide, striking about 025 degrees and dipping 80 to 85 degrees to the east. This shear is slightly discordant to the (folded) layering in fine-grained, weakly recrystallized quartz-mica phyllite and psammite which strike closer to north. Both the shear and layering are transected by a dextral slaty cleavage striking 300 degrees and dipping steeply northeast. A gently west-dipping fracture set occurs locally. Malachite and chalcanthite veinlets, layers and irregular disseminations with varying amounts of goethite and quartz occur discontinuously over 900 m as pinch and swell units accompanied by layered quartz veins in the shear zone. Some mineralization extends into the cleavage. Followed northwards the mineralized zone becomes more deformed and is disposed in 2 to 10 m long en echelon lenses, some of which may be boudinaged. Another ridge 1 km to the southwest contains malachite and quartz in a shear zone which may be a southern continuation. As described by Harms (1959) and Sofoulis (1967) the mineralized zone has been opened up by a vertical shaft (now 9 m deep) sunk into the east (hanging wall) side which joins the southern end of 53 m long drive (unstoped) serviced by two adits 30 m apart which enter from the west. Small gougings occur at the surface over the zone of best visible mineralization which is about 140 m long. There is no recorded production of ore. Six diamond drillholes, totalling 948 m were drilled by WMC from the east and inclined to the west-northwest at 120 m spacing along the strike of the shear zone. The mineralized intersections were 1.46 to 8.53 m in drilled width and assayed between 1.29 and 2.6 per cent copper, and consisted of quartz and chalcopyrite (?plus iron sulphides) replacing brecciated, bleached and silicified phyllite (Reid, 1959). Carbonated amphibolite and feldspar porphyry were also intersected in the drillholes. The base of the oxidized zone was encountered 9 to 15 m below surface.

The Tarraji (Mount Nellie South) prospect (16°34′40″S, 124°11′30″E) is 2.5 km south of Grants Find, of which it may represent a faulted strike extension. Sofoulis (1967) described an 0.3 m wide vertical quartz vein striking 320 degrees and containing disseminated malachite over a length of 4.6 m where costeaned. A shaft 7.6 m deep was sunk 20 m to the south, but failed to encounter mineralization.

An occurrence at Mount Nellie Southeast (16°35′00″S, 124°03′30″) is shown on the Yampi Sheet (Gellatly and Sofoulis, 1973) but no details are available.

The Wilsons Reward (Berylton, Wilsons Prospect, Wilsons Find) workings (16°37′30″S, 124°12′50″E) occur in a low, 650 m long arcuate ridge 7 km south of Grants Find and about 200 m west of the contact between the Halls Creek Group and the Lennard Granite to the east. In the summit of the ridge discontinuous lenses 1 to 10 cm thick and up to a few metres long of limonite, vein quartz and malachite accompanied by barren quartz veins and veinlets are largely confined to a west-northwest striking, steeply southwest dipping slaty cleavage developed in fine-grained quartz-muscovite psammite and pale grey siliceous phyllite. The mineralized quartz veins may be weakly rodded in a moderately south-plunging lineation resulting from the intersection of the cleavage with the folded layering, which strikes between northeast and north-northwest. A shaft containing water at 12 m and several small pits and costeans failed to find any encouragement. In 1959 WMC put four diamond drillholes totalling 755 m into the southern half of the ridge and encountered disseminated pyrite and pyrrhotite with subordinate chalcopyrite in quartz gangue. The best assay was 1.4 per cent copper over 3.8 m. Other holes intersected less than 0.83 per cent copper over 10 to 13 m. Fresh rock occurs at 15 to 21 m depth below surface. In general the mineralization at the surface is weaker and less continuous than at Grants Find.

The Monarch group (or workings, also called Berylton) of prospects (16°38′50″S, 124°13′30″E) are in a similar geological setting to Wilsons Reward. Shallow prospecting shafts have attempted to exploit north-northwest trending, subvertical pinch and swell quartz veins and veinlet networks carrying weak disseminations and stainings of malachite. A strong slaty cleavage developed in quartz-mica psammites, has a similar strike and a steep dip to the southwest. A production of 13.40 t of copper ore containing 2.80 t of copper was credited to two mineral leases in the area in 1915.

The Mondooma (Robinson River Copper Mine) prospect (16°49′30″S, 124°31′50″E) comprises malachite staining over a 190 m length of a subvertical quartz vein 0.9 to 4.6 m wide occupying a northwest-trending fault parallel to the schistosity of Halls Creek Group rocks (slate and phyllite) a few hundred metres from the edge of the Lennard Granite. A shaft 3 m deep and several costeans and pits disclose very disseminated mineralization only.

EAST KIMBERLEY REGION

Two occurrences on the Dixon Range Sheet (Dow and Gemuts, 1967) in the Olympio Formation at Osmond Creek (ca. 17°13′40″S, 128°19′00″E) and Frank River (17°27′00″S, 128°11′20″E) probably fall in the category of cupriferous quartz veins or shears, but no details are available. A copper occurrence at Mount Coghlan (17°59′00″S, 127°57′30″E) plots within dolomite of the Biscay Formation on the same sheet but again no further information is available.

In 1969 PMI reported copper shows at Mount Kinahan (18°08′10″S, 128°03′30″E) in three small vertical lenses in an east-northeast trending fault (the southern one of a pair) within Olympio Formation rocks. Chalcocite, cuprite and malachite occur with vein quartz in sheared country rock in lenses up to 30 m long and 3 m wide.

At the McLintock Range occurrence (18°51′10″S, 127°14′00″E) Dow and Gemuts (1969) described a high-grade lode 30 m long and up to 0.9 m wide containing secondary copper minerals in rocks of the Olympio Formation. To the northwest in the vicinity of the Mount Dockrell gold mining centre, PMI reported a number cupriferous quartz veins.

The following four occurrences are cupriferous shears within rocks of the Tickalara Metamorphics. Mabel Downs East occurrence (17°12′40″S, 128°13′10″E) is in dolomite, but no details besides location are known for the Froghollow Spring (17°16′10″S, 128°02′50″E) and Tickalara Bore (17°22′10″S, 128°00′20″E) occurrences. Harms (1959) described a lode containing cuprite, chalcocite and copper carbonates at a locality called Mount Slencke some 24 km northeast of Alice Downs homestead. The position of this occurrence is unknown.

MAFIC IGNEOUS ROCKS

At Roses Bore (17°40′40″S, 127°50′50″E) Dow and Gemuts (1969 p. 103) noted a quartz-copper carbonate vein in metadolerite assigned to the McIntosh Gabbro. The same authors recorded a discontinuous copper stained gossan 80 m long and up to 9 m wide associated with quartz in gabbro at Margaret River (18°39′S, 126°55′E).

GRANITOID ROCKS

The Secure Bay occurrence (16°32′10″S, 124°18′30″E) was discovered in 1966 by PMI who described a north-northeast striking quartz vein with sparse chalcopyrite blebs in bands 2 to 5 cm wide, scattered over a 150 m strike length in the Lennard Granite.

The Excelsior Range occurrence (ca. 16°36′30″S, 128°29′30″E) consists of vein quartz containing limonite disseminations and traces of copper carbonates within the Halls Creek Fault. Copper carbonates are also present in shears within undifferentiated granitoid rocks (Harms, 1959).

McHales copper show (17°05′10″S, 128°17′16″E) consists of sparse malachite and chalcocite in small lenses and seams in joints and shears within weathered, foliated hornblende granitoid (McHale Granite). There are also some very thin limonite-quartz veins with rare copper staining, which were costeaned.

The Corkwood West occurrence (17°23′20″S, 128°07′20″E) is on the southeastern margin of the Mabel Downs Granodiorite. No further details are available.

At Ord Gap (17°37′40″S, 125°53′10″E) malachite is present in shear zones and quartz veins cutting the Lennard Granite.

Minor shows of secondary copper minerals were reported by Dow and Gemuts (1969, p. 102) from the Bow River Granite at New Lamboo (ca. 18°27′00″S, 127°21′30″E), 1.6 km northeast of the New Lamboo homestead.

A group of mainly north-east trending quartz veins in a granitoid-country rock injection complex at Me No Savvy (18°29′S, 126°37′E) contain some chalcopyrite and secondary copper minerals. According to Dow and Gemuts (1969, p. 103) the veins are only about 5 to 20 cm wide and a few metres long. More extensive veins occur near shales of the Kuniandi Group which unconformably overlie the crystalline rocks. Diamond drilling in the area by Newmont in 1969 revealed interesting mineralization in only one of the six drillholes. The intersection was 1.52 m assaying 5.97 per cent copper at 42.7 m vertical depth in a south-dipping quartz vein 90 m long.

The Taylor River prospect (18°29′50″E, 126°30′30″E) consists of a 12 to 15 m wide and 37 m long quartz vein which trends west-northwest and is emplaced in Bow River Granite that is here concealed by alluvium. Several layers of chalcocite and malachite are visible in quartz exposed in the banks of Spring Creek. The alluvium was costeaned by PMI but no extensions to the vein or the mineralization were found.

In the Bullock Bore area (ca. 18°41′30″S, 126°32′30″E) there are cupriferous shears in granitoid rocks assigned to the Bow River Granite.

Malachite, chrysocolla and fluorite in small inclusions of metamorphic rocks surrounded by Bow River Granite and malachite within granitoid rocks, are reported from an area about 18 km southwest of New Lamboo homestead. The mineralization is apparently exposed over an area measuring 110 by 4.5 m.

WHITEWATER VOLCANICS

At the O'Donnell Range occurrence (16°26′30″S, 128°07′00″E) Dow and Gemuts (1969, p. 103) reported a thin, isolated quartz vein containing arsenopyrite and minor chalcopyrite. The vein is adjacent to a basic dyke and is only seen for 5 to 10 cm.

The Tumagee Yard occurrence (17°41′20″S, 127°24′30″E) consists of quartz veins carrying cupriferous limonitic gossanous material emplaced in the Greenvale Fault (Gellatly, 1967). The Goads Yard East occurrence (17°51′40″S, 126°41′00″E) is similar. Assays of gossanous material from both occurrences returned 700 to 5 000 ppm copper and up to 1 500 ppm lead (Gellatly, 1967).

Copper carbonate stains on the surface of a waterfall were reported by Dow and Gemuts (1969, p. 103) from the Whitewater Volcanics at the Dunham River Jump Up occurrence (16°27′30″S, 128°11′30″E). This mineralization may not be in a shear or quartz vein, but for want of any more specific information it is included here.

The occurrence at Camel Creek Yard (16°46′10″S, 128°26′20″E) is in the Castlereagh Hill Porphyry regarded as comagmatic with the Whitewater Volcanics (Plumb, 1968 p. 9). No other information is available.

MINOR COPPER MINERALIZATION IN LEAD-BEARING VEINS AND SHEARS

Two small deposits from the Mount Amherst area described by Blockley (1971b, p. 115) fall into this category. At the Dead Horse Creek prospect (18°18′30″S, 126°55′50″E), secondary copper minerals accompany quartz, calcite and galena, in a northwest-trending lode 94 m long and 3 m wide, emplaced in a granitoid-metamorphic rock injection complex. Two grab samples assayed 0.04 per cent and 0.25 per cent copper and small amounts of zinc in addition to the lead. A trace of copper carbonates accompany galena in an east-northeast trending silicified fault zone in metamorphic rocks (Halls Creek Group) at the Black and Glidden mine (18°23′30″S, 126°58′30″E).

COPPER-NICKEL DEPOSITS (TYPE E)

COPPER-DOMINATED MINERALIZATION

The only deposit in this category is at Bow River prospect (16°52′10″S, 128°20′00″E), in a very poorly exposed, gently undulating watershed between Turkey and Blackfella Creeks. Access can be gained via the Old Lissadell homestead track from the Great Northern Highway, then by turning north when 3.7km east of the Turkey Creek crossing. The deposit has been described by Blain (1967) and in several reports by PMI who investigated the area in the period 1965-1971.

The mineralization is in a metamorphosed gabbroid complex (McIntosh Gabbro) 6.5km long which intrudes garnetiferous gneiss assigned to the Tickalara Metamorphics. The complex strikes northeast, dips steeply north and is apparently intruded by contaminated Bow River Granite in the northeast. The only conspicuous outcrop in the mineralized area is of medium-grained quartz-feldspar-biotite gneiss containing almandine porphyroblasts and tectonic inclusions of semi-pelite, pelite and vein quartz; the foliation is nebulitic and convolute. This outcrop is to the northwest of the mineralization but it is intruded by weakly foliated, fine to medium-grained metagabbro. Most mineralization is in a massive, medium to coarse-grained metagabbro, and occurs as patchy disseminations of limonite accompanied in some areas by malachite and chrysocolla stains and disseminated grains. These limonitic-cupriferous areas are not as abundant as shown on Blain's map. Mineralized fractures up to 1cm thick are rare. No gossans were observed in the mineralized area which is 700m long (northeast) and 120m wide.

A series of diamond and percussion drillholes sunk by PMI intersected variably metamorphosed norite, gabbro and troctolite intruded by basic, pegmatite and aplite dykes. The gabbroids are layered and metamorphically foliated, and primary igneous fabrics are difficult to differentiate from superimposed metamophic features (e.g. granoblastic textures). All the drillholes encountered sulphides which are present as four styles of mineralization:

- (i) abundant pyrrhotite and minor chalcopyrite interstitial to silicate minerals (? primary sulphides);
- (ii) rare, thin massive bands of pyrrhotite with minor chalcopyrite;
- (iii) remobilized pyrrhotite and chalcopyrite as veins and stringers on the margins of younger intrusive dykes and
- (iv) remobilized pyrrhotite and chalcopyrite on joints and shears in the gabbroids.

Pentlandite generally occurs as flames in the pyrrhotite. In most drillholes there seems to be no preference shown for norite versus gabbro, though in one hole (DDH 115) the sulphides (intersected over 64 m drilled width) and particularly chalcopyrite occur in coarse-grained gabbro, the norite being barren. The average grade of the mineralization determined by the drilling was 0.20 per cent copper and 0.15 per cent nickel (Ni:Cu = 0.75).

NICKEL-DOMINATED MINERALIZATION

At the Limestone Spring prospect (16°56′40″S, 124°28′10″E) two small limonite gossans containing malachite, azurite and chalcocite and occurring 70 m apart have been costeaned, and an inclined shaft has been sunk to 6.1 m on one gossan (Harms, 1959). The gossans are at each end of a west-northwest striking outcrop of limonitic muscovite-chlorite schist (Halls Creek Group) which is intruded by a sill-like body of metadolerite (Woodward Dolerite). A narrow zone within the metadolerite contains disseminated pyrrhotite and chalcopyrite. Regional dip is 50 to 60 degrees to the south. Two diamond drillholes were put into a 730 m long induced polarization-soil geochemical (nickel, copper) anomaly by PMI in 1969. One of the drillholes intersected 5 per cent disseminated sulphides in the metadolerite, which assayed 0.39 per cent nickel and 0.20 per cent copper over a drilled width of 7.6 m. The zone of very high copper and nickel soil assays was only 60 by 15 m in plan.

The Corkwood nickel-copper prospect (17°19′30″S, 128°10′40″E) is just west of the Halls Creek Fault, and was discovered by Anglo American in 1972. The prospect is in the partially metamorphosed core of a basic igneous intrusion enclosed by high-grade gneiss and schist of the Tickalara Metamorphics. Pyrrhotite, pentlandite and chalcopyrite occur as narrow, massive bands and disseminations which are subparallel to the north-northeast striking regional foliation. Diamond drilling by Anglo American in 1973 returned grades of 0.1 to 0.5 per cent copper, 0.3 to 2.6 per cent nickel and 0.02 to 0.1 per cent cobalt over true widths of 1.5 to 4 m. Nevill (1974) compared the Corkwood prospect with the Bow River prospect described above.

The Sally Malay nickel-copper prospect (17°20′50″S, 128°01′20″E) is 3.7 km north of Dave Hill and 2.5 km west of the Great Northern Highway in hilly, dissected terrain. The prospect was discovered by Anglo American in 1974. A lens-shaped gossan striking east-west occurs at a contact between (i) relief-forming quartz-feldspar-garnet-biotite gneisses (Tickalara Metamorphics) containing mobilized and nebulitic areas, convolute folds, boudins, pegmatite and quartz segregations, and (ii) partially metamorphosed, largely undeformed olivine gabbro, troctolite and gabbro-norite which form subdued relief. Rafts of gneiss are found in the gabbroid rocks, which are evidently younger. Fresh sulphides are present 15 to 20 m below surface and consist of pyrrhotite (dominant), pentlandite, subordinate chalcopyrite and minor violarite, bravoite and pyrite. Magnetite is scattered throughout the massive sulphide, which is mainly a breccia ore containing country rock inclusions. The prospect is being evaluated by a major diamond drilling programme being implemented by Anglo American.

To the northwest of Sally Malay prospect, BHP discovered a small lens of iron-nickel-copper sulphides in a similar geological environment at the Keller Creek prospect (17°18′S, 127°58′E).

DISSEMINATED COPPER MINERALIZATION IN PORPHYRITIC FELSIC IGNEOUS ROCKS (TYPE D)

The only deposit in this category is the Mount Angelo South (Mount Angelo, MacIntyres) prospect (18°27′40″S, 127°28′10″E) which is 6 km at 127 degrees from Mount Angelo. The prospect lies about 500 m east of the northeast-trending Mount Angelo Fault which is marked by a line of prominent quartz veins and blows. The sequence of northeast-striking metamorphosed felsic volcanic rocks and psammitic sedimentary rocks present in the area of the Mount Angelo prospect extends southwestwards towards the Mount Angelo South prospect, but the rocks in the immediate area of the prospect are massive, medium grained, felsic and porphyritic. These rocks are poorly exposed and underlie several square kilometres of gently undulating terrain. Irregularly distributed felds-par and subordinate quartz (some ovoid to round) megacrysts are set in a fine-grained felsic matrix containing chlorite. Some chlorite occurs in lensoid aggregates. Rare patches of breccia (volcanic?) are present. The overall aspect of the rock is suggestive of a crystal tuff rather than a hypabyssal porphyry. Fractures in the rock may be coated with malachite and chrysocolla. Veinlets of quartz-limonite-malachite/chrysocolla up to a few centimetres thick are rare. Disseminated iron sulphides are common. There are no features about the deposit which define it as a porphyry copper style deposit, as has been suggested.

The prospect was discovered by S. J. MacIntyre in the early 1960's and first investigated subsurface by CRA in 1964 who drilled three diamond drillholes (totalling 200 m) that encountered mineralization of average grade between 0.19 and 0.35 per cent copper. In the period 1965-1967 PMI defined, by geochemical, induced polarization and magnetic surveys, a mineralized area measuring 650 by 490 m in plan (long axis north-south) which was tested by ten diamond drill-holes sunk to depths of 122 to 230 m. The best results were 12 m of 2.39 per cent copper and 4.3 m of 1.56 per cent copper, both from the same hole (DDH 203). Average assay values (excluding oxidized rock) for the remaining five drillholes intersecting mineralization were in the range 0.34 to 0.54 per cent copper. Resources of about 21 million tonnes containing 0.44 per cent copper were inferred by PMI.

CHAPTER 7

Bonaparte Gulf and Ord Basins

GEOLOGY

The onshore part of the Bonaparte Gulf Basin covers an area of some 7 000 km² and contains up to 6 km of Palaeozoic sandstone, limestone, shale, calcarenite, dolomite and tholeiitic basalt. This basin occurs along strike to the northeast of the Halls Creek Province and unconformably overlies the northeastern margin of the Kimberley Basin and the northwestern margin of the Victoria River Basin. Immediately to the south of the Bonaparte Gulf Basin is the Ord Basin lying mainly east of the Halls Creek Fault and extending over nearly 15 000 km². The Ord Basin contains a 2 km thick section dominated by Cambrian tholeiitic basalt, shale and limestone. The stratigraphy of the two basins is summarized in Table 16.

The Bonaparte Gulf Basin is structurally subdivided (Playford and others, 1975, p. 373) into (i) the Carlton Sub-basin in the north, which is faulted but little folded, and (ii) the smaller Burt Range Sub-basin in the south which is gently deformed by north-northeast trending faults and folds. The Ord Basin is subdivided into three sub-basins whose long axes trend at about 055 degrees. Two small sub-basins, the Argyle and Rosewood Sub-basins contain the full Cambrian sequence, whereas the larger Hardman Sub-basin also contains sandstone of possible Devonian age. The exposed Ord Basin outside these sub-basins consists almost entirely of Antrim Plateau Volcanics. Dips in the Ord Basin are gentle except along the western margins of the Hardman and Argyle Sub-basins.

MINERALIZATION (MAINLY TYPE B)

Known cupriferous mineralization is stratabound and is restricted to the Cockatoo Formation, Blatchford Formation, Hudson Formation, Headleys Limestone and Antrim Plateau Volcanics (Table 16). Occurrences in the latter two formations are the only widespread development of mineralization, which so far appears to be of no economic importance. The Redbank, Petes Find and Dunham River occurrences have been inspected by the writer.

CARBONATE HOST ROCKS

COCKATOO FORMATION

According to Plumb and Veevers (1971) the two prospects described hereunder occur in Point Spring Sandstone (Carboniferous), but the mixed carbonate-arenite lithology and folded and faulted nature of the beds is considered to be more consistent with the Cockatoo Formation.

The Redbank copper prospect (15°22′40″S, 128°39′30″E) is 45km north of Kununurra on the northeastern flank of the Pretlove Hills, in the western part of the Bonaparte Gulf Basin. The mineralization is associated with a west-southwest striking, elongate dome (some 500m long) of limestone overlain by fine-grained, pale buff sandstone. Dips on the flanks of the dome are 30 to 40 degrees. Thin lenses and laminae of malachite, cuprite, minor chalcocite and limonite occur at or near the limestone-sandstone contact on the western flank of the dome, as small areas up to a few metres long and 10cm thick over 250m of strike. Some veinlets and vuggy lenses occur lower in the limestone. No mineralization was seen in the sandstone. Small copper-stained limonite gossans also occur over 100m in a suspected fault on the east flank of the dome which juxtaposes northeast-dipping limestone and sandstone. The nature of the primary mineralization is unknown; what appears at the surface is unimpressive and has probably been redeposited by ground water into permeable sites.

Petes Find copper prospect (15°23′00″S, 128°40′00″E) is about 1.5 km southeast of the Redbank copper prospect in the same range of low wooded hills, and is adjacent to the Redbank lead-zinc prospect which has been costeaned and drilled by Placer-Conwest. Petes Find coincides with a 20m diameter vegetal clearing that is covered by rubble of fine-grained malachite. Immediately up hill (southwest) of the occurrence sandstone dips at 10 to 15 degrees to the northeast. Two shallow percussion drillholes were angled drilled into the prospect from the southwest and northeast, apparently with no result of interest. The visible mineralization is very feeble but enigmatic and again may bear little relation to the primary mineralization, perhaps representing mineral-bearing ground water circulation into permeable zones.

BLATCHFORD FORMATION

The Ragged Range occurrence (16°17′30″S, 128°20′00″E) was described by Plumb (1968, p. 27) as minor copper carbonates in joints in limestone of the formation exposed in the western scarp of the Ragged Range. Here the formation unconformably overlies the Antrim Plateau Volcanics which is reported to contain abundant celadonite (a green, non-cupriferous phyllosilicate) in the top few metres. The occurrence seems to be of no economic significance.

HUDSON FORMATION

Dow and Gemuts (1967) mentioned the presence of a 0.6 m thick bed of copper-stained limestone within the micaceous sandstone and siltstone of this formation in the Hardman Sub-basin. This is apparently the uppermost limestone bed of the formation. Dow and Gemuts (1969, p. 105) recorded the presence of small, very low grade patches of secondary copper minerals in this limestone at Mount Elder (17°13′40″S, 128°55′30″E).

TABLE 16. SUMMARY OF STRATIGRAPHY AND MINERALIZATION OF THE BONAPARTE GULF AND ORD BASINS

Age	Formation	Remarks And Mineralization
	BONAPARTE GULF BASIN	
Lower Permian	Keep Inlet Beds	Glacial
	unconformity	
Upper Carboniferous	Border Creek Formation	Sandstone and siltstone
	unconformity	
	Point Spring Sandstone	
Lower Carboniferous	Burvill Beds	Sandstone, shale and limestone
	unconformity	
	Milligans Beds	Shale and siltstone
	unconformity	
	Zimmerman Sandstone	
	Septimus Limestone	
	Enga Sandstone	
	Burt Range Formation	Calcarenite and sandstone
	unconformity	
Devonian	Ningbing Limestone	Stratabound lead-zinc-iron sulphides in Buttons Beds (sandy, silty limestone, now dolomitized)
	Cockatoo Formation	Isolated copper or lead-zinc occurrences in carbonates
	unconformity	
Lower Ordovician	Pander Greensand	
Middle and Upper Cambrian	Clark Sandstone	
	Pretlove Sandstone	
	Skewthorpe Formation	Dolomite, sandstone and shale
	Hart Spring Sandstone	
	Tarrara Formation	Sandstone, shale and dolomite
	Blatchford Formation[1]	Dolomite, copper carbonates in joints
	unconformity	
Lower Cambrian	Antrim Plateau Volcanics	Disseminated copper mineralization in some amygdaloidal basalts
	ORD BASIN	
Tertiary	White Mountain Formation	Chert, siltstone, marl
	unconformity	
Devonian?	Elder Sandstone	Cockatoo Fm equivalent?
	unconformity	
Middle Cambrian	Hudson Formation	Sandstone and siltstone, minor disseminated copper
	Panton Formation	Shale, siltstone and marl
	Linnekar Limestone	
	Nelson Shale	Gypsiferous in part
Lower Cambrian	Headleys Limestone	Chalcocite nodules and disseminations
	unconformity	
	Antrim Plateau Volcanics	Disseminated copper minerals in amygdaloidal flow tops and agglomerates

[1] Only developed in Ragged Range area, where the formation is unconformably overlain by the Cockatoo Formation.

HEADLEYS LIMESTONE

Disseminations, nodules and joint films of chalcocite, covellite and copper carbonates are reported to be widespread particuarly at the base of the formation (just above the top of the Antrim Plateau Volcanics) in a zone 12 to 120 cm thick (Harms, 1959). Gemuts and Smith (1968, p. 12) noted that such mineralization is also present at the top of the formation in the Gordon Downs Sheet area. Dow and Gemuts (1969, p. 104) regarded the main occurrences to be at Rosewood Wall and near Old Lissadell homestead (Lincoln Yard) in the Rosewood Sub-basin, and near Bungle Bungle outcamp in the Hardman Sub-basin.

The Rosewood Wall prospect (16°28′50″S, 128°58′00″E) consists of discontinuous, patchy copper staining on the face of a southeast-dipping limestone scarp over a 5 km strike length (Harms, 1959). Assay values of short channel samples from two short, shallow costeans (800 m apart along strike) were generally less than 0.3 per cent copper. Values of 11.5 per cent copper over 0.75 m and 2.55 per cent copper over 0.60 m thicknesses were obtained from the basal limestone in contact with the Antrim Plateau Volcanics (Harms, 1959). Chalcocite is the main copper mineral. The top portion of the volcanics assayed 0.53 and 0.60 per cent copper over 0.9 and 1.8 m respectively in the two costeans. There are no visible copper minerals in the volcanics which appear to be barren immediately below this copper-bearing portion. As suggested by Matheson and Teichert (1946) the copper may have been leached by ground water from the volcanics and precipitated by contact with the carbonates of the basal Headleys Limestone.

At the Lincoln Yard occurrence (ca. 16°32′S, 128°41′E) Harms (1959) observed flat-lying limestone immediately overlying the Antrim Plateau Volcanics in the bank of the Ord River. The limestone contained copper minerals over a 12 cm thickness traceable for 25 m along strike. This occurrence is now beneath the waters of Lake Argyle.

The Bungle Bungle outcamp occurrence (17°45′40″S, 128°18′50″E) is on the western margin of the Hardman Basin (Dow and Gemuts, 1967). No further details are available.

ANTRIM PLATEAU VOLCANICS

This formation consists of massive and vesicular-amygdaloidal, two pyroxene tholeiitic basalts with minor tuffs and agglomerates, and beds of stromatolitic chert. It is thickest and most widespread in the Ord Basin. The amygdales and geodes contain quartz (may be amethyst in part), chalcedony, calcite, prehnite, celadonite, zeolite group minerals, bituminous material and minor amounts of malachite, chalcocite, cuprite and native copper. Copper minerals may also occur as disseminations and thin laminae within the basalts, particularly in amygdaloidal or agglomeratic volcanic rocks.

Regional exploration by Metals Ex in 1968-1970 (Burt and others, 1970) over much of the formation's outcrop in the Ord Basin failed to disclose any mineralization of interest. Three types of copper occurrences were recognized:

(a) very extensive, but weakly mineralized (overall grade less than 0.1 per cent copper) agglomerate or amygdaloidal flow tops;

(b) local concentrations of copper minerals in flow tops perhaps associated with steeply dipping feeder structures (not established); and

(c) small copper shows associated with dark grey to black, brecciated, linear or semi-circular sideritic masses directly overlying the top most basalt.

The last type of occurrence was thought to be a result of intermittent fumarolic activity during the early deposition of the overlying Headleys Limestone. Local fragmentation and replacement of the limestone by iron-rich solutions with co-precipitation of copper-anomalous sideritic masses (up to 200 m in length) was envisaged. Thin acid pyroclastic and chert bands were found underlying some of these masses, and were also interpreted by Burt and others (1970) as expressions of terminal volcanicity. An induced polarization anomaly at such a prospect at Forrest Creek (17°37′20″S, 128°54′10″E) was drilled and abundant magnetite was encountered. Significant copper mineralization was not found.

The Dunham Crossing occurrence (ca. 16°06′00″S, 128°24′20″E) was described by Harms (1959) as being immediately east of the Great Northern Highway, about 3 km north of the Dunham River crossing. Loose boulders of prehnite contain small pieces of native copper. The boulders rest on low, rubbly hills of horizontal Antrim Plateau Volcanics.

The Dunham River occurrence (16°17′20″S, 128°14′30″E) is about 2 km north of Dunham River homestead. Malachite films are present on the surface of agate amygdales 0.5 to 3.0 cm in diameter which have weathered out of a poorly exposed, feldspar-phyric basalt flow. The occurrence is of no economic interest.

Harms (1959) mentions minor copper occurrences in the Behn Gorge area (16°28′S, 128°54′E) and near Wild Dog Soak (16°45′S, 128°54′E). A copper occurrence is shown on the Gordon Downs Sheet (Gemuts and Smith, 1968) at Coolibah Creek (18°14′20″S, 128°19′20″E), near an east-west fault. No further details are given.

CHAPTER 8

Pilbara Block and Archaean domes within the Hamersley Basin

SUMMARY AND CONCLUSIONS

The Archaean rocks of the Pilbara Block occupy a 60 000 km² area in the northwestern part of the State. 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 Lower Proterozoic Hamersley Basin which occurs immediately south of the Pilbara Block (Plate 1). Therefore, Archaean rocks similar to those exposed in the Pilbara Block probably underlie the whole of the Hamersley Basin. Mesozoic and Cainozoic rocks of the Canning Basin bound the block to the northeast.

The Pilbara Block comprises various metamorphosed supracrustal volcanic and sedimentary rocks arranged in faulted and folded, arcuate ('greenstone') belts around ovoid masses of granitoid and minor gneissic rocks (Plate 1). The contacts between the supracrustal and granitoid rocks are tectonic or intrusive, with most of the granitoid rocks being younger. Most granitoid rocks are deformed and metamorphosed, and yield radiometric ages in the range 2 900 to 3 100 m.y. (Oversby, 1976), but a suite of post-tectonic, highly differentiated potassic granitoids has a radiometric age of between 2 600 and 2 700 m.y.

A date of 3 453 ± 16 m.y. obtained from the U-Pb isotope system in zircon extracted from a dacite unit (Duffer Formation) is the best current estimate of the age of the oldest supracrustal rocks (Pidgeon, in press).

In terms of its size as a tectonic unit, the Pilbara Block has been the most productive copper-mining area in the State (Table 9). Whim Creek mine, the largest single producer in the State (Table 17), occurs in the western part of the block. Most copper mineralization is confined to the supracrustal rocks, which consist of a regional alternation of volcanic and sedimentary associations (Gee, 1975, p. 50) striking in a general east-northeast direction across the Pilbara Block. These rocks are subdivided into two, thick and extensive stratigraphic groups, the Warrawoona and Gorge Creek Groups (Lipple, 1975), and a third group, the Whim Creek Group (Fitton and others, 1975; Hickman, 1977), which is thin and restricted to a small area at Whim Creek.

The stratigraphy and cupriferous mineralization of these rocks is summarized in Table 18. It is stressed that the unconformities shown in this table are not regional in extent. Local unconformities and disconformities exist at all levels of the supracrustal sequence (Hickman, 1977, p. 54).

Stratabound copper-zinc deposits in metasedimentary or felsic metavolcanic rocks, are the single most important type of cupriferous mineralization in the Block in terms of (i) past mine production, (ii) widespread distribution stratigraphically and geographically and (iii) economic potential. However known major deposits are restricted to the top of the stratigraphic sequence in the West Pilbara, and many of the other examples seen to represent up-grading and concentration into structural sites such as fold hinges. A strong volcanic affiliation is evident for many deposits in metasedimentary (perhaps volcaniclastic in part) host rocks such as Whundo, Yannery Hill, Whim Creek, and Lennon Find. This is supported by an iron-copper-zinc—(rare lead)—sulphide paragenesis (cf. Sangster, 1972, p. 14). The internal mineralogical zonation typical of many Canadian, volcanogenic massive copper-zinc sulphide deposits is not recognizable in the well documented examples in the Pilbara, althought the differing strengths (and therefore differential mobility) of chalcopyrite and galena versus sphalerite and pyrite, may have led to modification of primary zonation during metamorphism and deformation. The copper:zinc ratios of seven deposits have a mean of 1.87 and a standard deviation of 2.16. Recrystallization and lack of data preclude positive identification of the chloritic schists, which enclose several deposits, as products of wall-rock alteration. Such rocks are far more widespread than the association mineralization in several cases (e.g. Whundo-Yannery, Jimblebar, Whim Creek); the only probable example of chloritization known to be genetically related to mineralization is at Mons Cupri. If deposits of this type are volcanogenic, the bulk of them, including strongly metamorphosed and deformed examples, appear to be distal in relation to a volcanic-exhalative metalliferous source. Mons Cupri is clearly a proximal volcanogenic deposit in a calc-alkaline volcanic centre.

Copper-molybdenum and copper deposits in fracture or quartz-vein stockworks rate next in importance using the same criteria as above. They are restricted to the East Pilbara and are commonly spatially and genetically related to porphyritic, felsic hypabyssal intrusions emplaced at a high structural level into the

Archaean crust. Disseminated pyrite-chalcopyrite (-molybdenite) mineralization occurs in stockworks in the intrusion and enveloping country rocks, which may be silicified, chloritized, carbonated or kaolinized. Some of this alteration may not be related to the mineralizing event(s). The deposits have some features in common with porphyry copper type deposits of Phanerozoic terrains. An apparent lack of associated water-rich, hydrothermal alteration in the intrusions and their envelopes may be an important deficiency in the Pilbara examples.

Cupriferous quartz veins and shears are ubiquitous and are unlikely to be of any economic importance, except perhaps as possible indicators of mobilized stratabound mineralization.

TABLE 17. MINE PRODUCTION OF COPPER FROM THE PILBARA BLOCK

Mine	Copper ore and concentrates (t)	Cupreous ore and concentrates (t)	Av. grade (%)	Contained copper (t)
Nullagine Sheet				
Boodalyerrie (Crown Lands)		0.95	13.20	0.62
Copper Gorge		2.13	35.00	0.75
Lennon Find	5.89		15.86	0.93
		28.92	13.84	4.00
Lionel	39.71		25.71	10.21
		372.10	15.47	57.56
Middle Creek	7.62		5.38	0.41
		4.04	8.88	0.36
Otways area		9.43	13.03	1.23
Marble Bar Sheet General				
Abydos		10.43	8.77	0.91
Breens	53.02		11.83	6.27
		289.60	12.16	35.22
Hazelby		10.81	7.50	0.81
Hazelby (SSW of)		16.32	9.52	1.55
Marble Bar South	11.20		14.91	1.67
		98.26	13.57	13.33
Mount Francisco		4.24	4.23	0.18
North Shaw	7.89		24.46	1.93
		5.06	15.89	0.80
Pilgangoora area (Crown Lands)		23.36	7.45	1.74
Stannum West		3.71	6.25	0.23
Wilson		13.81	15.02	2.07
Woodstock		9.09	8.12	0.74
Wyman Well (Crown Lands)		2.09	13.87	0.29
Copper Hills area				
Copper Hills	49.22		35.08	17.27
		15 455.67	12.68	1 958.88
Copper Hills West	422.95		24.52	103.70
		2.84	13.17	0.37
Emu Creek East		155.88	17.34	27.02
Kellys		609.69	19.47	118.71
Kellys District generally	0.54		55.56	0.30
Whim Creek-Mons Cupri area				
Mons Cupri	2 327.50		8.71	202.81
Mons Cupri NW		209.46	7.82	16.38
Rushalls	46.70		12.18	5.69
Western Hill		14.78	10.45	1.54
Whim Creek	76 889.60		13.48	10 365.21
		12 098.00	7.60	919.74
Pyramid Sheet				
Egina	550.99		19.19	105.73
		29.05	11.68	3.39
Evelyn	598.45		17.89	107.00
		59.65	7.06	4.21
Quamby and Kopje	15.24		26.97	4.11
		44.59	6.83	3.05
Mount Berghaus		1.20	9.17	0.11
Roebourne area				
Carlow Castle	1 041.07		15.71	163.53
		25.94	8.10	2.10
Ena	26.92		13.77	3.71
Fortune	419.01		19.18	80.36
		14.08	13.00	1.84
Good Luck	5.29		19.45	1.03
Lilly Blanche	1 030.25		18.73	193.01
Sundry claims	78.65		17.58	13.83
Whundo area				
Maitland		37.99	8.08	3.07
Whundo and Whundo West	7 358.00		25.96	1 910.00
		1 056.00	9.83	103.83
Yannery Hill	1 132.80		21.00	237.76
		1 911.80	12.87	246.05
Others				
Boodarrie Station		1.22	5.90	0.07
Jimblebar		84.09	8.37	7.04
Totals	92 118.51	32 716.28	[1]13.68	17 076.26

1. Overall average for copper and cupreous ore and concentrates combined.

STRATABOUND MINERALIZATION IN SUPRACRUSTAL ROCKS (TYPE A)

COPPER-ZINC DEPOSITS IN METASEDIMENTARY ROCKS

WHIM CREEK MINE

Introduction

The only deposit clearly in this category is at Whim Creek. Stratabound mineralization in more deformed and metamorphosed settings in which the origins of the host rocks are not readily apparent, are dealt with in a later section.

The major copper-zinc deposit at the Whim Creek (Whim Well) mine (20°50′50″S, 117°49′40″E) is 70 km east of Roebourne and 0.75 km southwest of the Whim Creek Hotel within freehold North Location 71 in the axial part of a synclinal structure of phyllite (Fig. 7). The deposit is 4 km north-northeast of the Mons Cupri copper-zinc deposit. The Whim Creek mine has been the largest single producer of copper in the State. Total mine production to 1977 is 76 889.60 t of copper ore averaging 13.48 per cent copper (10 365 t contained copper), and 12 098.00 t of cupreous ore averaging 7.60 per cent copper. All of this was oxidized ore and all but 13 per cent of it was dressed ore. The subordinate zinc mineralization has not been exploited.

History

The development of treatment methods at the mine is described in Chapter 1. A summary of exploration drilling carried out from 1910 to 1974 is given in Table 19 with some amplification in the text below.

The deposit was first mentioned in a report issued in July 1888 (Woodward, 1890, p. 27) but it was probably discovered a year or so earlier by a prospector, Phillip Saunders. Sporadic mining took place in 1889 and 1890, but production was not recorded. From 1891 to 1893 the Bateman syndicate exported 735.6 t of concentrates (30 per cent copper) derived from 6 744.5 t of oxidized ore mined averaging 15 per cent copper. The high cost of carting ore and supplies 100 km to and from the port of Cossack (north of Roebourne) and the low copper price at the time forced a closure. The former leasehold over the mine was converted to freehold North Location 71 in 1895, and in 1896 Prell and Company acquired the property and produced 2 967.9 t or ore (28.6 per cent copper) from 1898 to 1901 when the mine was closed again.

Whim Well Copper Mines Ltd gained control of the mine in 1906 and until the company ceased operations in 1919 64 484.2 t of ore and concentrates averaging 12.28 per cent copper were produced. The peak period of production was from 1909 to 1914 when an annual average output of 9 500 t of ore was attained. This was facilitated by the construction of a 22 km long tramline to a jetty at Balla Balla. This company carried out the first subsurface exploration of the orebody to the northeast (down dip) of the exposed and near-surface, oxidized part of the orebody (east shoot). In 1910 eleven vertical and inclined diamond drillholes (DDH1 to 11) totalling 1 032 m were completed and eight drillholes intersected the orebody in the sulphide zone yielding variable copper assays (details quoted in Low, 1963, p. 58-61). The best results came from DDH7 which intersected mineralization from 28.65 to 65.84 m drilled depth including a section 14.02 m long which averaged 9.64 per cent copper. This probably represents mixed primary and supergene sulphides.

In 1919 Whim Well Copper Mines Ltd was reconstructed as Pilbara Copper Fields Ltd which produced 2 693 t of ore and concentrates until operations halted in 1924. This company was engaged in the trial of several leaching plants involving a proposed water supply scheme financed by the Government (Blatchford, 1921; Wilson, 1928).

Finucane and Sullivan (1939a) inferred resources of 597 000 t of ore in place and 81 000 t of ore in dumps averaging between 3.35 and 3.76 per cent copper. In 1942 the Commonwealth Government financed seven diamond drillholes (DDH12 to 18) totalling 624 m, which were drilled (inclined southwards) northwest and northeast of the main shaft in the same general area as the 1910 drilling programme. All holes encountered sulphide mineralization most of which was dominated by iron sulphides and assayed less than 1 per cent copper (see Low, 1963, p. 62). The best intersections were of 1.52 m assaying 6.74 per cent copper (DDH12), and 6.40 m assaying 2.98 per cent copper (DDH18).

In 1949 I. Walters began production of cupreous ore (probably derived from dumps) amounting to 10 856 t averaging 5.78 per cent copper by the time that operations ceased in 1958.

North Broken Hill Ltd acquired an option over the mine in 1952 and completed eight vertical diamond drillholes (B1 to B8) totalling 304 m in areas of oxidized ore west and east-southeast of the main shaft. The cavernous and friable nature of the ground led to very poor core recovery, but most material obtained assayed less than 5 per cent copper (see Low, 1963, p. 63-66). Cuprite-bearing ore was apparently not encountered, and most drillholes probably failed to penetrate to the footwall.

Depuch Shipping and Mining Co Pty Ltd obtained options over the Whim Creek and Mons Cupri mines in 1959 and mined a 2 000 t trial parcel of ore intended for Japanese interests. The Rasa Trading Company of Japan and Dowa Mining Co Ltd purchased a majority interest and by the end of 1962 had completed twenty-four vertical diamond drillholes (WC1 to 24) totalling 4 998 m, and carried out some shaft sinking and underground development work. Of these drillholes eleven failed to intersect mineralization, five contained only traces of copper and the best intersections in the sulphide zone in the remainder were 19.81 m assaying 3 per cent copper (hole WC9), 15.24 m assaying 4 per cent copper (hole WC10) and 1.68 m assaying 22 per cent copper (hole WC3). Indicated in situ resources given by the company at this time were 294 600 t at a grade 'above 3 per cent copper', of which 98 200 t was oxidized ore and 196 400 t was sulphide ore. About 70 000 t of dump material was probably available then, and by March 1964 24 700 t of this material (grading about 2.5 per cent copper) had been treated by a new mill and flotation plant to yield 1 242 t of cupreous ore averaging 23.52 per cent copper (Table 20).

The Dowa Mining Co drilled a further thirty-six vertical and inclined diamond drillholes (WC101 to 136) totalling 5 670 m in the sulphide and oxidized zones in 1963-1964. As with their first drilling programme the assay data is incomplete. Best intersections in the sulphide zone were 8.23 m assaying 2.6 per cent copper (WC128), 4.18 m assaying 6.5 per cent copper (WC113), and 1.8 m assaying 30 per cent copper (partly chalcocite ?) in hole WC101. These two drilling programmes gave a good indication of the

TABLE 18. SUMMARY OF ARCHAEAN STRATIGRAPHY AND CUPRIFEROUS MINERALIZATION OF THE PILBARA BLOCK

Group	Lithology	Mineralization and remarks
3. Whim Creek Group	Phyllite, conglomerate and felsic metavolcanic rocks (largely pyroclastic), metabasalt at base.	1. Major stratabound copper-zinc deposits in phyllite and felsic agglomerate. 2. Rare cupriferous quartz veins.
	unconformity[a]	
2. Gorge Creek Group	*Upper part:* psammitic to pelitic metasedimentary rocks (phyllite, schist etc). *Lower part:* metabasalt (commonly pillowed) banded iron formation and chert, clastic metasedimentary rocks.	1. Small stratabound copper-zinc deposits in cores of folds (*upper part*). 2. Rare cupriferous quartz veins.
	unconformity[a]	
1. Warrawoona Group	Metabasalt (commonly pillowed), subordinate felsic metavolcanic rocks and ultramafic rocks, chert, tuffaceous phyllite and slate, carbonaceous slate, amphibolite, quartz-mica schist, quartz-chlorite schist, ultramafic schist, quartzite.	1. Small stratabound copper-zinc deposits in felsic metavolcanics, various schists, and carbonaceous phyllite. 2. Small copper-molybdenum and copper deposits in stockworks. 3. Abundant cupriferous quartz veins and shears. 4. Small nickel-copper deposits in ultramafic and associated rocks.
	contacts with the above rocks are intrusive or tectonic	
(i) Granitoid and gneissic rocks in ovoid masses.		Few cupriferous quartz veins and shears.
(ii) Discordant, massive or layered gabbroid intrusions[b]		1. Disseminated copper-nickel mineralization. 2. Cupriferous quartz veins and shears.

a. Unconformities may be locally developed here but also occur at other levels in the sequence. Such breaks are not of regional extent (cf. Taylor, 1976; Hickman, 1977).

b. Largely restricted to the West Pilbara, these intrusions appear to be late Archaean in age and may postdate the Whim Creek Group.

broad limits of economically interesting mineralization in the west and east shoot areas. This mineralization appears to be confined between the Jaffrey and Martin Faults (Fig. 7).

Whim Creek Consolidated NL acquired the plant and property in December, 1964. As part of a study of the resources of oxidized copper mineralization, sixty-seven vertical percussion drillholes (holes 201 to 270) totalling 1 183 m were sunk in 1965 in the west and east shoot areas. Probably 50 per cent of these drillholes failed to penetrate fully the oxidized zone. Furthermore incomplete assay data and poor sample recovery made assessment of the resources difficult using this drilling programme. Copper values were typically in the range 0.5 to 5.0 per cent. During 1967, diamond drilling totalling 333 m and rotary-percussion drilling totalling 1 784 m was completed (holes 67-1 to 67-27 and RV1 to RV36). This drilling programme was mainly directed towards an evaluation of the down dip part of the west shoot (oxidized and sulphide zones). The result was an increase in estimates of indicated resources. The presence of some 376 000 t of sulphide mineralization averaging 2.5 per cent copper was estimated in 1967.

Induced polarization anomalies about 500m east-northeast of the main shaft and positioned east of the Martin Fault (Fig. 7), were tested by three diamond drillholes (69 WCD1 to 3) totalling 465 m in 1969. No mineralization was encountered although two of the drillholes may not have been deep enough. The anomalies were probably caused by pyritic phyllite. A further nine diamond drillholes (69 WCD4 to 12) totalling 766m tested possible down dip extensions of sulphide mineralization in the eastern part of east shoot (about 100m east of the main shaft). The results were encouraging. Up to 6m of massive sulphides were encountered, and the highest assay value from the mineralized zone was 21.3m of 3.89 per cent copper (69 WCD12) which included a section averaging 8.25 per cent copper over 8.23m.

Westfield Minerals (WA) NL (a subsidiary company of Whim Creek Consolidated NL) reviewed all existing data in late 1969 and concluded that further drilling would be required (a) for satisfactory definition of measured resources of known sulphide and oxide mineralization, (b) for testing of contiguous extensions to this mineralization, and (c) to obtain suitable samples of oxidized ore for metallurgical tests. Since 1965 there had been plans to establish the feasibility of an open cut mining and/or leaching operation at Whim Creek.

From December 1969 to August 1970, 116 drillholes (69 WCD13 to 17; 70 WCD1 to 70; 70 WCD100 to 105; 70 WCP1 to 35) totalling 5 745m and com-

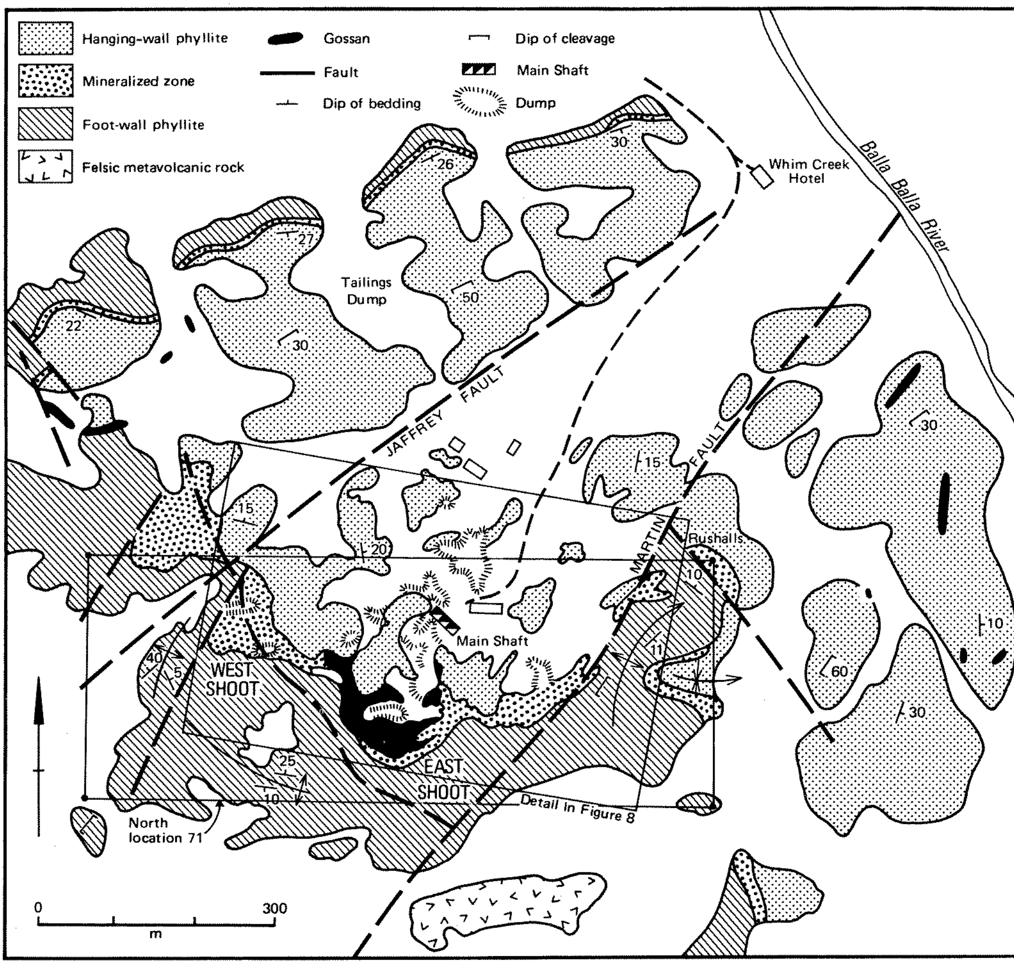

Figure 7. Geological map of the Whim Creek area

prising 1 915m of percussion drilling and 3 830m of diamond drilling, were put down on a 30m grid in three areas. These areas are (i) the sub-surface portion of west shoot, (ii) the east shoot to the east of a north-south line through the main shaft and east to the Martin Fault, and (iii) the eastern half of the exposed gossan at east shoot (Fig. 8). Following this drilling and a revision of the geology, measured resources were recalculated at 132 448t of oxide mineralization averaging 4.8 per cent copper and 294 834 t of sulphide mineralization averaging 2.5 per cent copper based on a cut-off grade of 1 per cent. Total resources are therefore 427 282t of 3.21 per cent copper. Subsequent drilling (Table 19) has tested geological and geophysical targets in outlying areas without success. The known mineralization of economic interest still remains confined between the Jaffrey and Martin Faults as indicated by the 1962-1964 drilling programme. However, the newer drilling clearly demonstrated the detailed distribution and grade of oxide and sulphide mineralization to be very erratic.

Metallurgical and leaching tests of both oxide and sulphide mineralization have been carried out since 1970, with a view to treating mainly oxide, carbonate and supergene sulphide mineralization (dominantly cuprite and malachite) extracted from a proposed open pit, about 400m long (east-south east) 200m wide and up to 40m deep. The pit would be sited on west and east shoots. Concentration of the low grade material in dumps has also been investigated. The latest published resources are 1.0Mt of sulphide mineralization averaging 1.51 per cent copper and 1.33 per cent zinc and 1.65Mt of oxidized mineralization averaging 1.68 per cent copper (0.3 per cent copper cut off for both ore types). In addition there is 50 000t of oxidized mineralization containing 3.25 per cent copper at the surface.

Geology

The Whim Creek copper-zinc deposit occurs in the upper part of a mixed mafic to felsic metavolcanic and pelitic metasedimentary sequence termed the Whim Creek Group (Fitton and others, 1975) as redefined by Hickman (1977). This Group forms the major part of the northeast-striking Whim Creek Belt which is 80 km long and 5 to 10 km wide, and is bordered by the Caines Well Granite to the northwest and metasedimentary rocks of the Gorge Creek Group to the southeast (Hickman, 1977, Fig. 28). Stratigraphic nomenclature within the Whim Creek Belt is discussed by Hickman.

The margins of the Whim Creek Belt appear to be largely faulted. Major open folds plunging at low to moderate angles to the northeast or southwest, and a moderate to steeply southeast-dipping slaty cleavage characterize much of the belt. At Whim Creek (Fig. 7) and Mons Cupri this cleavage is deformed by east-striking folds of variable plunge which may exhibit a weak axial planar, fracture or crenulation cleavage. Small kink-style folds occur locally and deform both these older structures. Boudinage structures have been observed in the mineralized zone. The bedding at Whim Creek defines an open, but complex synclinal structure which plunges northeast. This structure contains a well developed slaty cleavage which dips southeast on the limbs of the syncline, but dips to the east or northeast in much of the axial zone (Figs. 7 and 8). This is where the bulk of the mineralization occurs.

The sequence containing the mineralized horizon has been described as the 'Whim Creek argillites' by Koehler (1974) and as 'essentially unmetamorphosed black slate, siltstone and minor sandstone beds' by Reynolds and others (1975). Slates by definition are metamorphosed, generally having attained the low greenschist facies of regional metamorphism (Hobbs and others, 1976, p. 403). In the field the pelitic rocks commonly display a phyllitic sheen caused by recrystallization of phyllosilicates and they are referred to here as phyllites. The phyllite sequence structurally and stratigraphically overlies a felsic metavolcanic sequence called the Mons Cupri Volcanics (Fitton and

TABLE 19. HISTORY OF EXPLORATION DRILLING AT WHIM CREEK MINE

Operator	Period	Number of drillholes	Total drilled length	Best intersection	Remarks
Whim Well Copper Mines Ltd	1910	11 diamond DDH1-11	1 032 m	14.02 m of 9.64% Cu	Mixed primary and supergene sulphides
Mines Department of WA	1947	7 diamond DDH12-18	624 m	6.40 m of 2.98% Cu	Primary sulphides
North Broken Hill Ltd	1952	8 diamond B1-8	304 m	6.10 m of 8.5% Cu	Oxidized ore, 18% recovery
Dowa Mining Company Ltd	(a) 1962	24 diamond WC1-24	4 998 m	15.24 m of 4.0% Cu	Sulphide zone
	(b) 1963-64	36 diamond WC101-136	5 670 m	4.18 m of 6.5% Cu	Slightly oxidized sulphide
Whim Creek Consolidated NL	(a) 1965	67 percussion 201-270	1 183 m	5.18 m of 20.2% Cu	Oxidized ore and supergene sulphide
	(b) 1967	44 holes (various) (i) 67-1 to 27 (ii) RV-1 to 36	2 117 m	(i) 3.9 m of 7.93% Cu and 10.1% Zn (ii) 6.1 m of 5.7% Cu	Sulphide oxidized
Westfield Minerals (WA) NL	(c) 1969	12 diamond 69 WCD1-12	1 231 m	21.3 m of 3.89% Cu	Primary sulphide
	(d) 1969-70	116 holes (various) 69 WCD13-17 70 WCD1-70 70 WCD100-105 70 WCP1-35	5 745 m	(i) oxidized 7.0 m of 11.6% Cu (ii) sulphides 14.0 m of 3.49% Cu	1970 feasibility study for oxide and sulphide resources
	(e) 1970	27 percussion 70 WCP 36-62	733 m	9.1 m of 1.1% Cu	Best of outlying geological and IP targets
	(f) 1972	4 diamond 72 WCD1-4	295 m		Pyritic mineralized zone in outlying areas, very low assays
	(g) 1974	71 percussion 74 WCP1-71	1 647 m		Fill-in drilling, test of outlying mineralization (low assays), test of proposed dump sites and existing tailing sands

Grand total drilled length = 25 579 m

others, 1975), which crops out to the south. The phyllite is in turn unconformably overlain by mafic metavolcanic rocks to the north.

The phyllite is a fine-grained, reddish-brown weathering rock (dark grey-green where fresh) composed of quartz, chlorite and muscovite with minor and accessory pyrite, sphalerite, chalcopyrite, rutile sphene and epidote. Coarser grained, more siliceous clastic laminae and beds may be commoner in phyllite ('footwall phyllite') below the mineralized zone. Otherwise the phyllite is monotonous and in the absence of the mineralized zone 'footwall phyllite' cannot generally be distinguished from 'hangingwall phyllite'. However, Reynolds and others (1975) note that pyrite is the common accessory sulphide in hangingwall phyllite, but is replaced by chalcopyrite in the footwall. A lithic, tuffaceous metasedimentary rock crops out sporadically at the base of the phyllite sequence, and averages 10 to 14 m in thickness in the area of west and east shoots, but thins to 1.5 to 3.0 m to the west, north and east (Reynolds and others, 1975). In general it is conformable and can be traced around most of the syncline (Fig. 7). In contrast to the rest of the sequence the mineralized zone is lithologically heterogeneous. Chlorite-rich phyllite is the commonest rock type, accompanied by siliceous phyllite, recrystallized pyritic chert, cream-weathering, poorly sorted, chloritic or carbonaceous, felsic tuffaceous (?) rocks, and massive layers, veinlets and disseminations of fine to coarse-grained sulphides. The proportions of these rock types making up the mineralized zone is very variable. Weathering of the sulphides has promoted kaolinization of the zone in outcrop. The mineralized zone is well exposed 150 m south-southwest of the main shaft on the summit of the hills encircling the trough of the syncline.

Mineralization

Mineralization of economic interest is confined to the area between the Jaffrey and Martin Faults, and by a steepening of the dip of bedding from about 20 to 25 degrees to 50 degrees to the northeast which is reported to limit potential ore in that direction (Reynolds and others, 1975). The area of potentially economic copper-zinc mineralization thus measures about 550 m along strike and 200 m down dip (Koehler, 1974). Thin beds of sphalerite extend about 60 m down dip of this area. An open anticlinal structure apparently separates two northeast-plunging synclines thereby defining the west and east shoots, although mineralization is continous between them (Fig. 9).

In order of decreasing abundance, the major sulphides are pyrite (cobalt-rich), pyrrhotite, chalcopyrite and sphalerite. Pyrrhotite is a commoner in east shoot, whereas sphalerite is commoner in west shoot. The sphalerite is a low-iron variety with zinc:iron ratios from 7:1 to 20:1. Galena, magnetite and arsenopyrite occur in minor or accessory amounts. At the margins of potential ore, chalcopyrite and pyrrhotite are replaced by pyrite or pyrite and sphalerite (Reynolds and others, 1975). The top contact of mineralization is sharp, whereas the bottom contact is diffuse and is arbitrarily defined by assay values in many places. Reynolds and others (1975) recognized three modes of occurrence of sulphides as follows:

(i) upper zone—finely layered (2 to 4 mm) pyrite and sphalerite with minor galena; grain size 0.1 to 0.5 mm; colloform textures present;

(ii) middle zone—medium grained, massive pyrite/pyrrhotite and chalcopyrite; and

(iii) lower zone—disseminated chalcopyrite

Examination of drill cross-sections indicates many exceptions to this mineralogical sequence. Individual concentrations of sulphides appear to be lenses rather than beds as detailed correlation between drillholes is rarely possible. Textures in the sulphides are very variable ranging from fine-grained, laminated massive sulphides to coarse chalcopyrite veins and sulphide-cemented microbreccia (Fig. 10 and Appendix 1). The gangue is chlorite-rich phyllite, vein quartz, chert and siderite; in massive sections it may occur as inclusions in the sulphides. The laminated massive sulphides seen by the writer are well recrystallized and contain short, fine-grained monomineralic lenses 1 to 2 mm thick rather than laterally extensive laminations. The breccia and vein textures, and contorted, foliated massive sulphides are probably the result of limited deformation and remobilization during the tectonism and low-grade metamorphism which is also manifested in the country rocks. A complex mixture of primary (e.g. colloform) and secondary textures is the result.

Two oxidized zones are developed above primary sulphide mineralization (Fig. 9) as follows:

(a) leached oxide zone: malachite, azurite, chrysocolla, cuprite and limonite; zinc is totally leached, but lead may occur as carbonates and sulphide; and

(b) mixed oxide-primary sulphide zone: cuprite and malachite with minor pyrite, chalcopyrite and accessory sphalerite and galena

TABLE 20. PRODUCTION OF CUPREOUS ORE AND CONCENTRATES FROM THE WHIM CREEK—MONS CUPRI AREA SINCE 1960[1]

Year	Tenement	Registered name	Ore and concentrate (t)	Average Assay (% Cu)	Total value for period ($A)
	Whim Creek mine				
1963	Location 71	Depuch Shipping and Mining Co Ltd	497.46	28.75	
1964	Location 71	Depuch Shipping and Mining Co Ltd	744.80	20.02	206 742.5
	Mons Cupri Northwest mine[2]				
1961	LTT 1449H	M. Alac	209.46	7.82	5 285.10
	Western Hill mine[2]				
1961	PA 284	W. Simpson	14.78	10.45	615.80

1 Details of earlier production are given by Low (1963, p. 67)
Total production figures are given in the text

2. Informal name

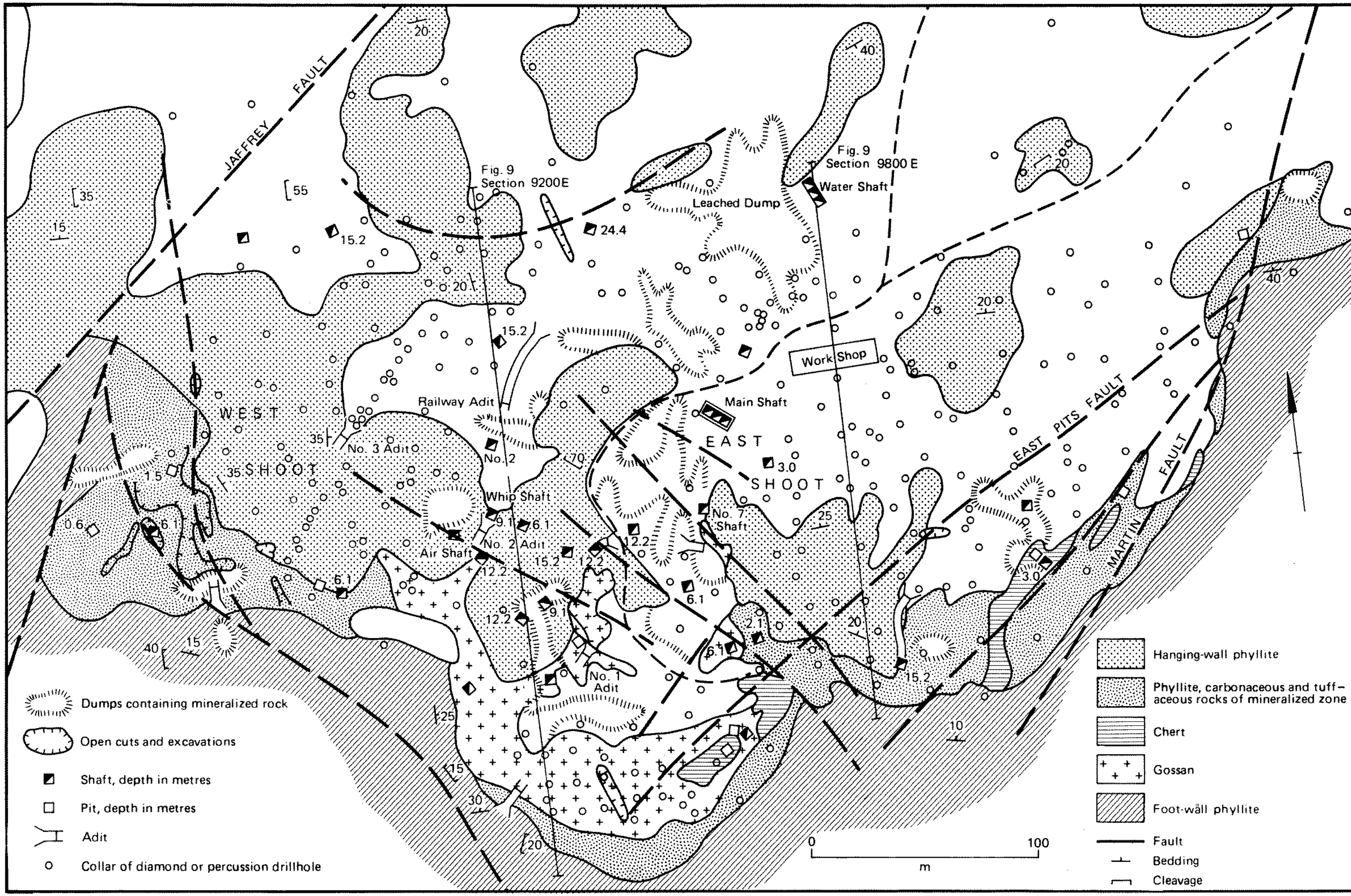

Figure 8. Geology and surface workings at Whim Creek mine

The contact between zones (a) and (b) is gradational but the contact between (b) and the primary sulphide zone is sharp. Zone (b) is commonly about 15m thick. Minor occurrences of atacamite, chalcanthite, native copper, bornite, digenite, chalcocite and covellite have been reported. The copper-rich parts of zones (a) and (b) probably represent (in part) an oxidized ancient supergene sulphide zone (T. Koehler, pers. comm. 1977).

Genesis

Koehler (1974) concluded that the sulphide mineralization was syngenetic-diagenetic and that, together with iron and magnesium silicate detritus, and chemical precipitates, it was derived from a nearby exhalative (acid volcanic) centre similar to the one at Mons Cupri. Reynolds and others (1975) reached similar conclusions and related exhalation to a waning phase of acid volcanism. A comparison with Kuroko-type base metal deposits in Japan was also made despite the absence of proximal volcanic rocks and the lack of any evidence for hypogene ore fluid channelways at the mine.

In attempting to decipher the origins of the mineralization it is important to differentiate secondary physical and chemical modifications of the mineralized zone from primary depositional features. For example, it is not clear to what extent the high chlorite content of the host rocks of the mineralized zone is (a) a primary depositional feature (favoured by Koehler, 1974), (b) due to wall-rock alteration (i.e. 'chloritization') by ore fluids, (c) the result of sulphide-silicate reactions during metamorphism or (d) some combination of these processes. Koehler (1974) found that some chlorites in and adjacent to the mineralized zone were iron rich.

The phyllite sequence is weakly sulphidic and may therefore have supplied a little sulphur, but the bulk was more likely introduced into the sedimentary basin with the metals in chloride or bisulphide complexes. The original nature of the metal zonation may have been complicated by secondary effects (including perhaps penecontemporaneous slumping), but the apparent upward and lateral zonation from copper to zinc sulphide (and pyrite) is comparable with volcanogenic deposits (e.g. Rosebery, Tasmania; Abitibi region, Canada), though the locus of mineralization need not be related to an eruptive centre (cf. Green, 1976).

The heterogeneous and partly volcaniclastic nature of the mineralized zone is clear evidence of a major interruption in the invariant and stable depositional conditions responsible for the bulk of the phyllite sequence. The pyritic cherts in the mineralized zone may also be precipitates of exhaled solutions.

In the absence of any further study, it seems reasonable to regard the deposit as a modified volcanogenic-exhalative type deposited distally from any active volcanic centre (which may not necessarily relate to the ore fluid channelways).

Minor deposits

Minor copper deposits exploited in the Whim Creek area include the following.

1. Rushalls (20°50′40″S, 117°50′00″E) at the north east corner of Location 71 (Fig. 7).
2. Federal City (20°50′10″S, 117°50′00″E), about 1.2 km north of the Whim Creek mine in an alluvial flat.
3. Stranger or Croydon Road (20°50′24″S, 117°50′50″E), about 2.0 km east of the Whim Creek mine.

All three deposits were described by Woodward (1911, p. 70-71). Rushalls mine (ML10) is the only one in the same mineralized zone as the Whim Creek mine, and is situated in the faulted nose of a gently northeast-plunging anticline (Fig. 7). The mineralized section in the workings was reported to be less than a metre thick, composed of copper oxide and carbonates with quartz and kaolin. The mine was worked in 1899 when 20.3 t of copper ore (average 15 per cent copper) were exported, and again in 1907 when 26.4 t of ore (about 10 per cent copper) were produced. At Federal City Woodward reported that small but rich cupriferous veins were worked but the shafts had fallen in and there were no signs of ore at the surface. The Stranger or Croydon Road workings (ML33) consist of collapsed open cuts (formerly 3 to 4 m deep) and two shallow shafts (Fig. 11) which exploited small, malachite-stained limonite quartz veins and lenses. These are subparallel to the subvertical cleavage and layering in phyllite that is silicified marginally. Some 10 t of copper ore (25 per cent copper) were exported in 1899. In 1973 Australian Inland Exploration drilled from the east two inclined (50 degrees) drillholes totalling 210 m with targets beneath the workings. The first hole intersected 2.8 m of 0.67 per cent copper, 0.83 per cent lead and 9.00 per cent zinc in 'siliceous rhyolite' but core recovery was only 24 per cent. The second hole was stepped back to the east but failed to encounter mineralization.

COPPER-ZINC DEPOSITS IN METAVOLCANIC ROCKS

MONS CUPRI MINE

Introduction

The Mons Cupri mine (20°52′40″S, 117°48′20″E) occurs on a steep-sided 90 m high hill, 70 km east of Roebourne and 4 km south-southwest of Whim Creek mine, in a north-east trending tract of dissected hilly terrain. This tract is coincident with the supracrustal rocks of the Whim Creek Belt. The general geological features of this belt are described above. The deposit is within coarse felsic fragmental metavolcanic rocks of the Mons Cupri Volcanics.

History

The deposit was probably discovered by J. S. Hicks in 1897. Between 1899 and 1901 Balla Balla Copper Mines Ltd produced 2 041 t of copper ore averaging 8.26 per cent copper which was either smelted on site or exported. Whim Well Copper Mines Ltd acquired the property in 1907, continued underground development, and by 1917 had shipped out 286.5 t of ore averaging 11.96 per cent copper. This was the last production from the mine. In 1938 Finucane and Sullivan (1939a) surveyed the mine workings and geology, and described the copper ore as small veins and irregular patches of chrysocolla, malachite and azurite in fractures within 'basic tuff with numerous fragments of acid tuff'. Acid volcanic ash, tuff, breccia and flows were also noted. The deposit did not receive further attention until 1965 when Whim Creek Consolidated NL was granted a Temporary Reserve (TR) covering Mons Cupri and Whim Creek. In 1968 Australian Inland Exploration Co. Inc. (subsidiary of Texasgulf) obtained an interest in the TR and a major exploration programme began in May, 1968. The first drillhole sunk intersected 30 m of copper-lead-zinc mineralization. A sum of 172 drillholes totalling nearly 32 000 m were subsequently put down on geophysical geological anomalies. This indicated resources in 1973 of 10.9 to 13.6 Mt of 1 per cent copper (oxidized and primary mineralization) including 1 Mt of 2.5 per cent

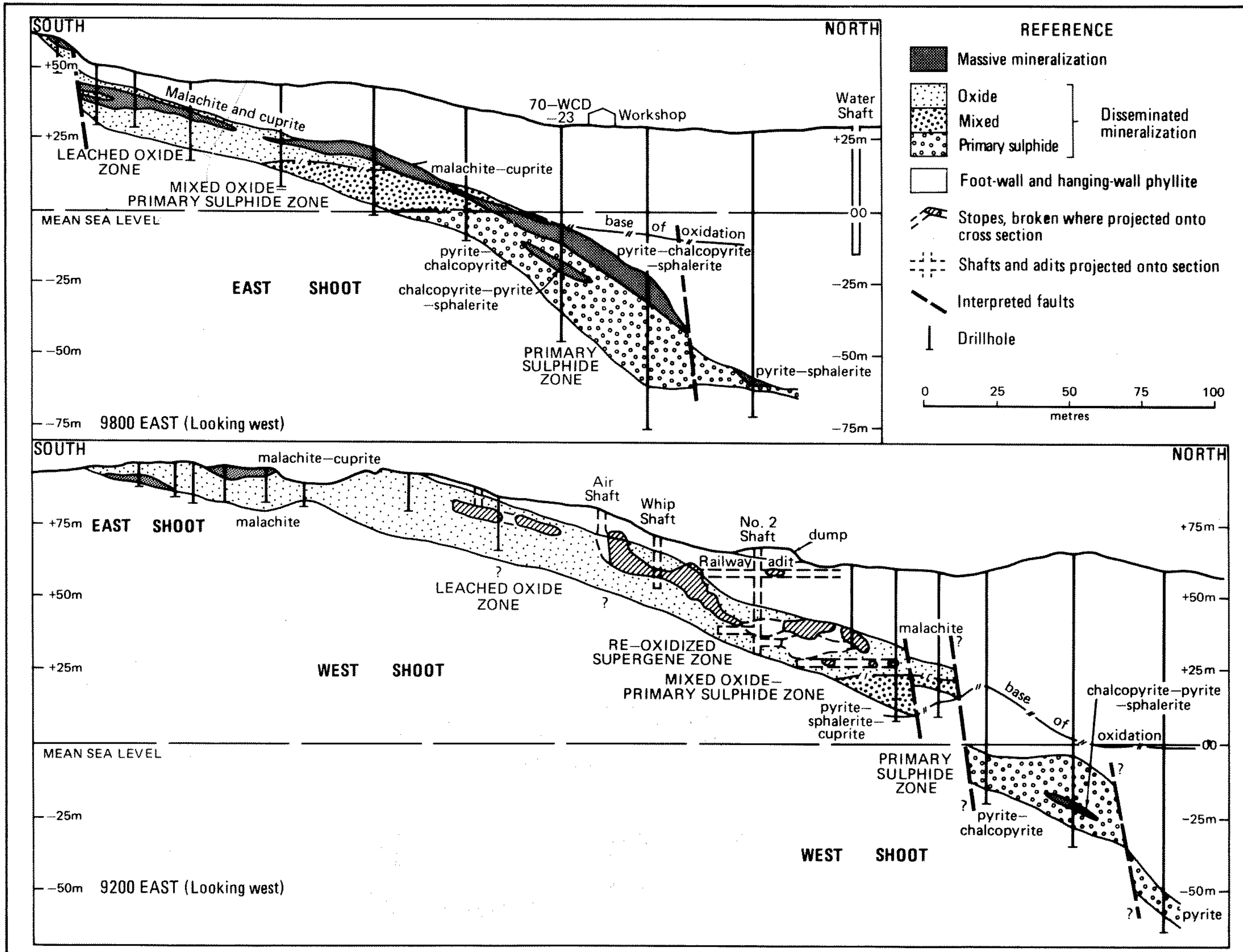

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Figure 9. North-south cross sections through east and west shoots at Whim Creek mine

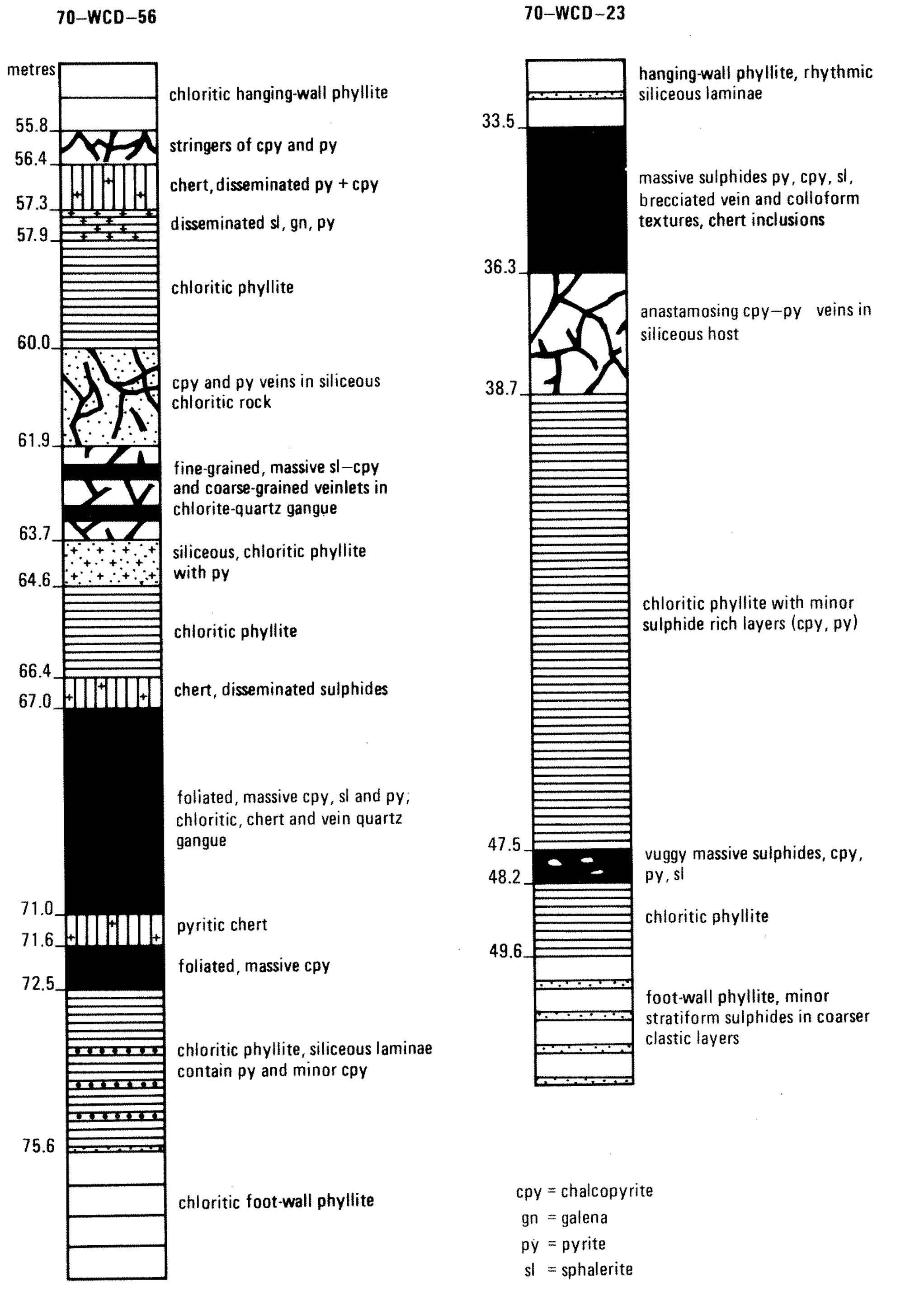

Figure 10. Diagrammatic logs of the mineralized zone in diamond drillholes 70-WCD-56 and 70-WCD-23, Whim Creek

lead, 3.6 per cent zinc and 62 g/t silver. Miller and Gair (1975) interpreted a discovery of lead-copper mineralization made on the western side of the hill by Finucane and Sullivan (1939a), as the edge of a west-dipping bed of felsic tuff and chert containing massive and disseminated lead-zinc-copper mineralization. This bed was considered to form a capping to the disseminated, stockwork-like copper mineralization in coarser fragmental rocks, which historically had been exploited in the main mass of the hill.

Geology and Mineralization

The nature of the volcanic pile (Mons Cupri Volcanics), which is characterized by rapid facies changes, semi-concordant penecontemporaneous subvolcanic felsic intrusives, and later hypabyssal felsic intrusives, leads to many problems in geological interpretation. These difficulties are compounded by upper greenschist facies regional metamorphism, and the local development of complex and intense deformation and metasomatism. The result is a multiplicity of interpretations of stratigraphy and ore genesis (e.g. Miller and Gair, 1975; M. E. Smith, 1975; Sylvester, 1976). The stratigraphic scheme proposed by Sylvester (1976) is summarized in Table 21. The major departures from previous ideas resulting from Sylvester's work are as follows:

(i) The Mount Brown Rhyolite (unit 7a, Table 21) is regarded as a subvolcanic intrusive associated with high level granitoids (unit 7b), both of which intrude the mineralized sequence (unit 4); formerly the rhyolite was placed in the layered sequence. The porphyries (unit 3) in the layered sequence are chemically distinct from the Mount Brown Rhyolite.

(ii) Mineralogical zonation is not recognized in the ore and specifically a capping of stratiform lead-zinc-copper mineralization is absent. This mineralization is stratabound and may have capped the copper deposit but is now only present on its margin.

(iii) A strongly chloritized zone enclosing the mineralization in the felsic agglomerates cannot be shown to be pipe-like in three dimensions, although it may have been so, prior to deformation. Some of this alteration probably post-dates the mineralization as similar alteration affects the Mount Brown Rhyolite.

If Sylvester's conclusions are accepted it is clearly not feasible to regard Mons Cupri strictly as a volcanogenic copper-lead-zinc deposit of the Kuroko or Abitibi type, in which stratiform massive lead-rich or zinc-rich sulphide overlies a genetically related chloritic pipe containing disseminated iron-copper sulphides (Miller and Gair, 1975, p. 200-201). However several elements of the deposit are comparable, and tectono-metamorphic modification may have obscured further like features.

The host rock to most of the copper mineralization is a metamorphosed massive felsic agglomerate rich in feldspar porphyry fragments (many identifiable with the 'ore porphyry' unit 3, Table 21) with subordinate rhyolite, granitoid and mafic volcanic

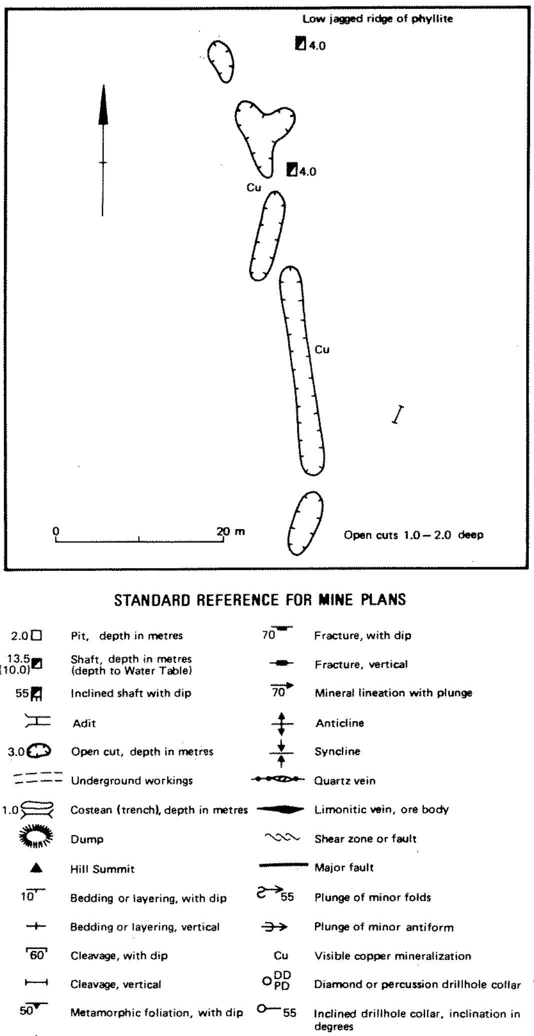

Figure 11. Surface plan of Stranger workings and standard reference for all large scale mine plans

TABLE 21. STRATIGRAPHY OF THE MONS CUPRI VOLCANICS

7a. Massive spherulitic rhyolite (Mount Brown Rhyolite) and grey to black feldspar porphyry; 7b. Leucocratic granite-adamellite with glassy quartz	6. Andesite-dacite-rhyolite flows and pyroclastics; chert and slate-phyllite (as at Whim Creek)	
	5. Laminated shallow-water clastic rocks including reworked tuffaceous material [d]	MONS CUPRI VOLCANICS
	Copper plus minor lead-zinc mineralization in upper part of unit 4	MONS CUPRI VOLCANICS
	4. Dacite-rhyolite agglomerate [c] (550 m)	MONS CUPRI VOLCANICS
	3. Dacite-rhyolite porphyry intrusives [b] ('ore porphyry') (200-400 m)	MONS CUPRI VOLCANICS
	2. Dacite-rhyolite flows and tuffs [a]	MONS CUPRI VOLCANICS
	1. Andesite-dacite flows and tuffs [a] (Warambie Basalt)	

(Modified from Sylvester, 1976)

a. Combined thickness 350 m
b. Partly equivalent to the 'Domal Rhyolite' of Miller and Gair (1975) and Smith (1975), though Smith does not regard it as domal
c. Equivalent to 'Mons Cupri rhyolite fragmental' (Miller and Gair, 1975)
d. Includes the 'Cistern Rhyolite' and 'Cap Shale' of Miller and Gair (1975) and M. E. Smith (1975)

Rock nomenclature refers to pre-metamorphic lithology fragments which are commonly angular but may be partly rounded. There are no fragments resembling the Mount Brown Rhyolite. Some of this rock is variably chloritized giving it the appearance of a green mafic rock in outcrop. The chloritized zone is lens shaped in outcrop with dimensions of 700m (east-west) by 125m maximum. Where alteration is most intense in the centre of the chloritized zone, all primary structure is obliterated. Well layered, fine-grained to medium-grained meta-tuffs, and reworked tuffaceous rocks and thin, discontinuous chert horizons occur locally near the top of the agglomerate and may also be chloritized and mineralized. In outcrop malachite, chrysocolla and limonite occur as disseminations and in a stockwork of veins and veinlets, many of which carry hydrothermal quartz and are sub-vertical. A slaty cleavage is developed in the host rocks and strikes about 290 degrees and dips steeply south.

The hill contains numerous pits, open cuts, drives and crosscuts (Finucane and Sullivan, 1939a, Plate 5) put in on surface shows of secondary, disseminated-stockwork copper mineralization. The main workings are an upper adit 170 m long and trending 006 degrees which cuts right across the hill some 22 m below the summit, and a lower adit 145 m long and trending 008 degrees which enters the hill from the north about 46 m below the summit.

Thin lenses of massive sphalerite-galena with subordinate chalcopyrite have been intersected in the upper, marginal parts of the chloritized zone. The bulk of the primary copper mineralization occurs in disseminations, stockwork quartz veinlets and rare, coarse-grained massive lenses and patches in the main mass of the chloritized zone. The mineralized zone appears to taper out at 160 m depth below surface. Miller and Gair (1975, Fig. 2) indicate that the bulk of the mineralized zone or 'pipe' assays 1 to 3 per cent copper, with a core of poorer mineralization averaging 0.5 per cent copper. The southern margin of the zone is shown as zinc rich (up to 3 per cent zinc). The sulphide assemblage is commonly dominated by chalcopyrite with subordinate pyrite, minor galena and sphalerite and trace amounts of bismutite, tetrahedrite and linnaeite. Pyrrhotite is absent. The sulphide minerals have recrystallized along with silicate and oxide minerals during metamorphism.

Texasgulf have investigated the feasibility of establishing an open-pit mining operation on the main Mons Cupri deposit, based initially on the mining and heap leaching of the oxidized portion with indicated resources of 4.08 Mt of 0.77 per cent copper.

At Mons Cupri Northwest mine, 600 m northwest of the main deposit, small pits and open cuts exhibit disseminated secondary copper mineralization in chloritized, graded-bedded volcaniclastic metasedimentary rocks striking 310 degrees and dipping 25 degrees south. The mine produced a small amount of cupreous ore in 1961 (Table 20). The rocks are folded and cut by a slaty cleavage subparallel to their strike but dipping 45 to 50 degrees south. Limonite and secondary copper-mineral-bearing veinlets up to 1 cm thick occur in the cleavage and bedding, forming an anastamosing pattern. This general area is termed the 'western pits mineral zone' by Miller and Gair (1975).

The Western Hill mine is about 1 700 m southwest of Mount Brown in cleaved, southwest-striking felsic metavolcanic rocks at a contact with a metagabbroic complex. A small amount of cupreous ore was extracted from shallow workings in 1961 (Table 20).

COPPER GORGE PROSPECT

The Copper Gorge (Mickles) prospect (21°36′20″S, 120°20′50″E) is 20 km at 226 degrees from Baroona Hill. The prospect was discovered by W. Mickle and Party in 1964 who took out PA's 868, 878, and 882, plus PA 879 covering an occurrence 1.3 km southwest of the main prospect on PA 868. A production of 2.13 t of cupreous ore assaying 35.00 per cent copper is recorded from PA 879 in 1965. A cyclic mafic to felsic metavolcanic sequence punctuated by three chert horizons dips northwest at an average of 20 to 25 degrees. This sequence has been assigned to the Duffer Formation of the Warrawoona Group, and it occurs at the eastern end of the McPhee Dome (Hickman, 1975a). Several northerly-trending fault sets complicate the geology. The terrain is deeply dissected, nevertheless most rocks are weathered and partly kaolinized and bleached.

The local stratigraphy is as follows:

Unit
8. Pillowed metabasalt, some highly magnesian
7. Felsic metavolcanic and pyritic chert
6. Pillowed metabasalt
5. Chert, disseminated pyrite, some breccia, 0 to 9 m
4. Rhyolitic-andesitic flows and tuffs 90 m
3. Chert, pyritic, partly silicified tuff 0 to 6 m
2. Rhyolitic-andesitic flows, tuffs and breccia, *Cu*, 150 m
1. Metabasalt 150 m

Iron-copper-zinc-silver mineralization is best developed in the top 30 m of unit 2 in fractured rhyodacite-andesite flows and fragmentals as pyrite-chalcopyrite-sphalerite-quartz (or dark chalcedony) disseminations and veinlet stockworks. Small pods up to 6 m thick containing 20 to 30 per cent pyrite but only up to 2 or 3 per cent chalcopyrite have been encountered in drillholes. The surface expression of this mineralization is a sporadic malachite-limonite impregnation accompanied by rare grains of cuprite. Most copper shows are confined to an area between two north-trending faults about 2 km apart. Weaker and more localized shows of copper in fractures, disseminations and amygdales occur about 15 and 100 m above the base of unit 2 within this same area. All surface manifestations of mineralization are unimpressive.

Cominco carried out 415 m of percussion drilling in 1966, but only encountered short mineralized intersections up to 1 per cent copper. An inferred resource estimate of 0.5 Mt of 0.5 per cent copper was made. A total of 10 diamond drillholes put down by Asarco (7) and Kennco (3) only yielded a best intersection of 1.2 m of 0.29 per cent copper and 5.2 per cent zinc. This drilling was openly and irregularly spaced. The results obtained so far give little encouragement for further work.

BIG STUBBY ZINC-LEAD-COPPER-BARIUM PROSPECT

This prospect (21°13′00″S, 119°45′10″E) is 6 km south of Marble Bar in a rugged, hilly tract of steeply southwest dipping, andesitic-rhyolitic metavolcanic rocks intruded by mafic dykes and sills on the south-western margin of the Mount Edgar batholith (Hickman, 1975a). The rocks contain a subvertical cleavage or foliation. The mineralized zones are thin and impersistent laterally, and occur within fine-grained to medium-grained tuffaceous units in coarse rhyolitic fragmental rocks in the main area of interest. Diamond drilling carried out so far has yielded disappointing results (see Reynolds and others, 1975 for details) with copper assays of only 0.1 to 0.3 per cent over 1.5 to 4.3 m. There seems to be little field evidence to substantiate contentions (Reynolds and others, 1975) that, (i) the deposits occur within a large caldera subsidence area marked by a radial pattern of mafic dykes, and, (ii) that rhyolite domes intruded the coarse felsic breccia sequence.

COPPER DEPOSITS IN METAVOLCANIC ROCKS

OTWAYS COPPER PROSPECTS

R. H. Otway pegged claims in the area (21°34′S, 120°16′E) in 1965 and in the same year produced 5.36 t of cupreous ore assaying 13.50 per cent copper from MC 806. The prospects are sited in the northern half of the McPhee Dome, 10 km west-northwest of Copper Gorge, in carbonated and chloritic, pillowed amygdaloidal metabasalt or andesite accompanied by chloritic felsic metavolcanic rocks and altered gabbro-pyroxenite intrusives. The sequence appears to dip gently northwards and is cut by east-northeast and east-southeast striking kaolinized shear zones which may contain siliceous, limonitic and rarely copper-stained material.

Visible copper occurrences and shallow workings occur in an east-northeast striking mineralized zone 400 m long and up to 90 m wide. Mineralization occurs in the shears and is also disseminated throughout the rock. In December 1966 Conwest drilled twenty-two percussion drillholes inclined westwards and totalling 1 014 m along two north-northwest-trending lines 60 m apart. Several drillholes averaged around 0.5 to 0.7 per cent copper assays over their drilled length (about 45 to 60 m), the best intersection being 1.38 per cent copper over 6.1 m (hole OS3) in chalcopyrite-bearing meta-pyroxenite. Other rock types contained only traces of copper mineralization. In 1972 Kennco drilled eleven percussion drillholes totalling 571 m in and around the mineralized zone, but only encountered traces of chalcopyrite (subordinate to pyrite) in the pillowed mafic metavolcanic rocks and underlying felsic metavolcanic units. The mineralization has obviously not been tested in depth, however ground magnetic, induced polarization and Turam surveys carried out by Kennco failed to find any anomalies.

A prospect 3 km to the northwest of Otways in metabasalt produced 4.07 t of cupreous ore assaying 12.40 per cent copper in 1965 (MC 824).

BRIDGET NORTHEAST PROSPECTS

These prospects occur on the northern margin of the McPhee Dome (21°31′20″S, 120°19′30″E) in a sequence of pillowed metabasalt, bedded chert-jaspilite and metadacitic fragmental rocks dipping north at 20 to 45 degrees, intruded by quartz-albite-hornblende porphyry and biotite tonalite dykes and stocks. Anglo American investigated the area in 1972-1973 and found pyritic mafic flows and bedded pyritic horizons (assaying less than 2 000 ppm copper), and malachite-chrysocolla bearing quartz veins and stringers in silicified zones of metabasalts, some of which were associated with porphyrydikes. The primary mineralization is pyritic and these prospects illustrate the common enrichment of trace amounts of primary copper in the oxidized zone and in surface gossanous expressions.

DEPOSITS IN MEDIUM-HIGH GRADE METAMORPHIC ROCKS

INTRODUCTION

The mineralization described here is in deformed and recrystallized rocks which generally lack primary textures diagnostic of origin. In some cases the mineralization has been partly mobilized out of an originally stratabound location. In common with the host rocks, the structure of mineralized zones may be complex (e.g., folded, rodded and boudinaged). In most examples the host rocks are probably derived from volcanic or volcaniclastic rocks of felsic composition. The deposits are described from east to west.

COONDAMAR CREEK COPPER-LEAD-ZINC PROSPECTS

These prospects (21°55′50″S, 120°39′50″E) are 57.5 km at 095 degrees from Nullagine in east striking quartz-chlorite-sericite-feldspar schists (probably metasedimentary) of the Mosquito Creek Formation (upper Gorge Creek Group), occurring between two north-trending faults. A visit has not been made to this area and details derive from the results of the Carpentaria exploration programme in 1974 (Guj and Nenke, 1975). Two gossanous localities occur 500 m apart along strike, where the country rocks strike north-northwest, parallelling the eastern fault. At the southern gossan locality there is a 20 m long and 3 m thick limonitic gossan containing malachite, azurite, chrysocolla, cuprite, hydrozincite, smithsonite and cerussite. This gossan assays up to 27 per cent copper. Short intervals of pyrite, chalcopyrite, sphalerite and galena mineralization were encountered down plunge from the gossan which is interpreted as occupying the core of a tight north-northwest plunging syncline. The best intersection in primary sulphides was 1.80 m (true thickness) assaying 1.1 per cent copper, and 2.51 per cent zinc. At the northern gossan locality, the mineralization at depth is largely pyritic despite the presence of malachite with limonite in the gossan and as stains in the foliation of the schists.

LENNON FIND ZINC-LEAD-COPPER PROSPECTS

This area (21°21′30″S, 120°14′00″E) is on the southeast margin of the Mount Edgar batholith, 19.2 km at 106 degrees from Mount Edgar homestead. Mineralization is present in a sequence of moderately southeast dipping, lineated quartz-muscovite schist (Warrawoona Group) about 600 m from the edge of the batholith. This schist may contain, additionally, biotite, chlorite, feldspar and amphibole, with minor units of garnetiferous quartz-feldspar-dark amphibole rock, porphyroblastic andalusite-quartz-mica schist and quartzite (recrystallized chert). An account of the area was given by Blockley (1971b, p. 142-145). Recorded production is 5.89 t of copper ore averaging 15.86 per cent copper (0.93 t copper) and 28.92 t of cupreous ore averaging 13.84 per cent copper.

The mineralization occurs in carbonate, chlorite and calc-silicate-rich quartz-feldspar-mica rock of very variable composition, associated with recrystallized chert. The host rock forms an horizon up to 2.0 m thick, traceable discontinuously along strike for nearly 4 km near the structural top contact of the siliceous sequence (probably of felsic volcanic origin) with a sequence of amphibolite and mafic schist to the southeast. There is little visible copper in surface outcrops and old workings. At the main old workings shallow drives along the strike reveal boudinaged chlorite-rich units up to 20 cm thick accompanied by concordant vein quartz. The main host rock is a fine-grained pyritic quartz-sericite schist containing a fine down-dip mineral lineation. A concordant limonitic horizon 5 to 40 cm thick carries weak malachite staining and extends discontinuously for a strike length of 900 m. A channel sample over 1.8 m taken from these workings by Cominco averaged 2.40 per cent copper, 7.25 per cent zinc and 0.03 per cent lead. Lower values were found in five inclined diamond drillholes totalling 351 m put down by Cominco in 1969 at intervals along a 2.4 km strike length. The best intersection was 1.22 m assaying 1.37 per cent copper, 2.8 per cent lead and 8.3 per cent zinc in DDH701 collared 490 m northeast of the main old workings. The primary sulphides are fine to medium-grained pyrite (cobaltiferous), with subordinate sphalerite and galena, and minor accessory chalcopyrite (Appendix 1). Barite is an important gangue mineral in places. The mineralization contains significant amounts of silver (up to 180 g/t).

Subsequent drilling by other operators has failed to find further encouragement from this extensive but very thin and copper-poor carbonate-chlorite-sulphide-quartz horizon. Six diamond drillholes put into the 900 m long zone by Cominco and Serem—Project Mining average 0.41 per cent copper, 1.81 per cent lead, 7.54 per cent zinc and 102 g/t silver over a true width of 1.91 m.

JIMBLEBAR COPPER-ZINC PROSPECT

The Jimblebar (Copper Knob) prospect (23°27′10″S, 120°08′40″E) is 5 km at 289 degrees from the old Jimblebar gold battery, in the northeastern part of the Sylvania Dome in the western, arcuate prolongation of a small east-west oriented supracrustal belt. The rocks in this prolongation comprise strongly foliated and/or lineated amphibolite, siliceous amphibolite, quartzite, quartz-feldspar-mica schist, banded iron formation, ultramafic schist and quartz-albite-chlorite-hornblende-biotite schist. Critical mineral assemblages indicate that regional metamorphism attained upper greenschist facies conditions (Barley, 1974). This latter schist may be garnetiferous (spessartite-almandine), is green when fresh and red when weathered, and appears to be geochemically anomalous in copper discontinuously over a strike length of perhaps 10 km. The average outcrop width of the schist is 200 m, the main schistosity commonly dips steeply southwards, and a penetrative mineral lineation plunges about 60 degrees towards 220 degrees at the prospect.

Subconcordant zones of disseminated iron-copper-zinc mineralization (limonite-malachite staining) occur throughout this ridge-forming schist unit, but at the main prospect, shows are concentrated in the summit. Limonite veinlets form an anastamosing network and malachite staining appears rarely on outcrop surfaces. Quartz segregations and late tectonic veins carry malachite staining marginally. Very shallow prospecting pits tested two 5 to 10-m-wide zones 30 m apart and less than 100 m long containing very sporadic malachite in veinlets and disseminations in limonitic veins and pods up to 10 cm thick. An 11-m-long adit, bearing 180 degrees was driven into the ridge top from the northern side into the northernmost of these two zones, but only traces of copper mineralization were encountered.

Production dates from 1959 and 1962 and amounts to 84.09 t of cupreous ore averaging 8.37 per cent copper. This ore contained malachite plus cuprite, tenorite, chalcocite, bornite and chalcopyrite. The primary sulphides comprise about 45 per cent pyrrhotite (monoclinic) intergrown in aggregates with chalcopyrite (40 per cent), with sphalerite and pyrite making up the remainder (Barley, 1974). The nickel:cobalt ratios of iron sulphides examined by Barley (1974) were low (<0.5) indicating a magmatic-hydrothermal origin for the mineralization. The mineral assemblage and copper:zinc ratio (5.7) are typical of several volcanogenic sulphide deposits (cf. Sangster, 1972).

Exploration by Vam Ltd and Endeavour has demonstrated enrichment in the oxidized zone (about 50 m deep). Four inclined diamond drillholes totalling 636 m were put down in 1971 in a 300-m-long by 50-m-wide zone of secondary enrichment on the ridge. The best intersections in the oxidized zone (CRO1) assayed 1.34 per cent copper over 22.9 m (including 6.1 m of 3.42 per cent copper). The primary sulphides averaged 0.15 to 0.25 per cent copper over the entire drilled widths with peak values of 1.81 per cent copper and 0.48 per cent zinc over 9.1 m (CRO2) and 0.91 per cent copper and 0.89 per cent zinc over 1.9 m (CRO4). Eighteen inclined percussion drillholes totalling 968 m were then drilled in 1972 in a larger, partly concordant area 600 m long and 100 m wide. Six of the drillholes intersected mineralization assaying more than 0.5 per cent copper, values being in the range 0.65 to 1.55 per cent copper. Including values in diamond drillhole CRO1 indicated resources of 1 Mt of 0.77 per cent copper were estimated for this oxidized mineralization. A deep inclined diamond drillhole (CRO5) drilled in 1973 demonstrated a continuance down dip of a zone several hundred metres wide assaying 0.16 to 0.38 per cent copper. Similar values were encountered in another diamond drillhole (CRO6) which intersected mineralization visible in a costean at the foot of the western end of the ridge.

A large volume of disseminated very-low-grade copper mineralization is present, but in the absence of any indications of important higher grade concentrations the prospect appears to have no economic potential. Higher grade lenses could exist in the mineralized schist unit elsewhere along its strike.

HAZELBY COPPER PROSPECT

This prospect (21°03′40″S, 118°56′30″E) also known as Pilgangoora (Low, 1963), is 6.1 km at 073 degrees from Coffin Bore and occurs within a sequence of mafic to ultramafic schists (Warrawoona Group) in a narrow north-striking supracrustal belt termed the Pilgangoora Syncline by Hickman (1975a). Thin beds (up to 10 m thick) of recrystallized chert, black slate or carbonaceous phyllite and metamorphosed felsic pyroclastic (?) rocks punctuate this sequence, define gently to moderately south-southwest plunging open folds, and contain local concentrations of copper mineralization.

The main workings (Fig. 12) are shallow and occur in the hinge of a major syncline plunging at about 30 degrees towards 185 degrees, which has an axial plane schistosity dipping steeply east. The mineralization consists of a limonitic bed perhaps up to a few metres thick carrying minor malachite and azurite. This bed is on the hanging wall side of a silicified black slate in chlorite-quartz-pale amphibole schists. Recrystallized chert and cherty tuff (?) and pyritic, pale schist also occur on dumps. A production of 10.81 t of cupreous ore averaging 7.5 per cent copper has been recorded.

The same chert-slate bed thins on the limbs of the structure and three very shallow prospecting pits 250 m southwest of the main workings mark a similar copper-stained limonitic bed, here only 60 to 80 cm thick and in the hinge of a minor fold. Drilling by Esso in 1974 to 1975 indicated surface enrichment of copper in both areas, the primary mineralization being dominated by up to 30 per cent foliated pyrite over a few metres, in graphitic phyllite with very minor or accessory amounts of chalcopyrite, sphalerite, pyrrhotite and arsenopyrite.

Some 7 km south-southwest of Hazelby the production of 16.32 t of cupreous ore assaying 9.52 per cent copper is recorded for P.A. 2680 (J. Matheson) in 1963. This location has not been visited and the best fix available is 21°07′35″ south, 118°55′00″ east.

In 1964 23.36 t of cupreous ore (7.45 per cent copper) was produced from Crown Lands in the Pilgangoora area.

EGINA COPPER MINE

The Egina mine (21°05′50″S, 118°13′10″E) is 11 km at 094 degrees from Mount Satirist in folded and cleaved, easterly striking metasedimentary rocks of the Mallina Formation (upper Gorge Creek Group). The main slaty cleavage strikes east and dips steeply north, but a fracture cleavage strikes north and dips west. The country rocks are mainly pale grey-green, fine-grained to medium-grained, clastic siliceous metasedimentary rocks and carbonaceous phyllite, in which the layering generally strikes north-northeast and dips steeply southeast. In the vicinity of the mine workings (Fig. 13) folded chloritic and amphibolitic rocks are intimately associated with iron-poor banded iron formation, which may be pyritic. Minor folds plunge moderately to the east and the shape of the open cuts indicates that the ore shoots conformed with these structures. Individual shoots are up to 50 cm thick and consist of massive limonite with malachite and atacamite and a little vein quartz. Lenses of vein quartz occur separately.

The mine has produced 550.7 t of copper ore (105.70 t copper) and 29.05 t of cupreous ore assaying 11.68 per cent copper. The copper ore was smelted at Mons Cupri. Underground mining levels were established at 9.14 and 15.24 m depths, the former level being the most productive (Sullivan, 1939).

In common with Coondamar Creek and Hazelby prospects, it appears that local, economically unimportant concentration of weak stratabound mineralization has occurred in fold hinges. Weathering has further enhanced copper values in dominantly iron sulphide mineralization.

EVELYN COPPER MINE

The Evelyn (Croydon, Lady Evelyn) mine (21°05′50″S, 117°50′40″E) is situated 5 km at 059 degrees from Croydon homestead. The country rocks are folded and lineated, but generally north-northeast striking, tremolite-chlorite-quartz schist, talc-chlorite schist, tremolite schist all occupying a small area in the core of a major anticline which is dominated by recognizable siliceous metasedimentary rocks (upper Gorge Creek Group). The workings occur in a narrow zone 280 m long (Fig. 14) in the rock types listed. A mineral lineation plunging at 35 to 55 degrees towards the northeast is the dominant structure, and as at the Egina mine this is reflected in the shape of excavations in the open cut, indicating that the ore shoots are probably rodded. Malachite, chrysocolla and azurite are disseminated in massive limonitic material with a small admixture of vein quartz in dumps around the main workings in the south. Small lensoid limonite pseudogossans (less than 1 m long) outcropping on the ridge to the north are also suggestive of small rodded shoots of largely iron sulphides.

Total production of copper ore is 598.45 t (107 t copper) and 59.65 t of cupreous ore most of which averaged 7.06 per cent copper. An ore shoot was exploited on levels at 13.7 m, 19.8 m and 25.9 m depth. The shoot was 11 m long and 4.9 m thick at the surface (now the open cut), 13.7 m by 2.4 m at the 13.7 m level, and 19.8 m long and 1.8 m thick on the 19.8 m

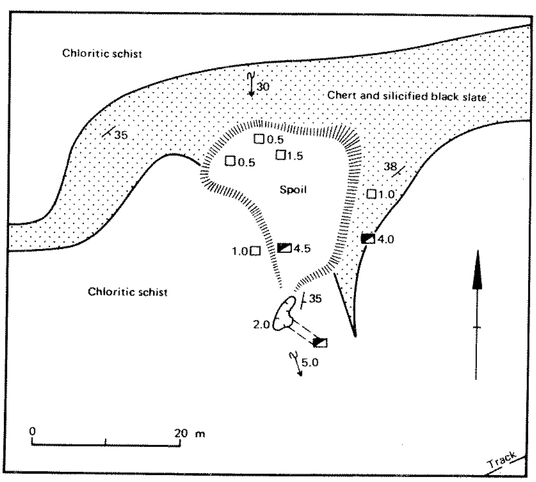

Figure 12. Surface plan of Hazelby workings

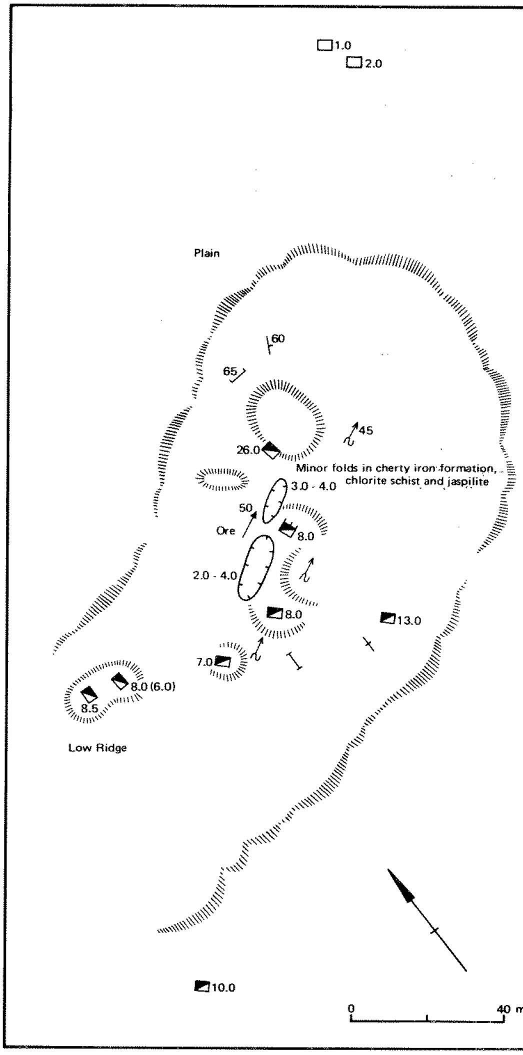

Figure 13. Surface plan of Egina mine

level (Woodward, 1911, p. 91). At the 25.9 m level primary sulphides consisting of chalcopyrite, marcasite and sphalerite were encountered. Supergene sulphides occurred between 15 and 26 m depth. The zinc-rich nature of the primary ore discouraged further mining. A sample of surface gossan assayed 15.3 per cent copper, 0.56 per cent lead, 780 ppm zinc and 526 ppm silver.

Mineralization appears to be localized in small, steeply plunging shoots perhaps representing structural concentration of lower grade stratabound mineralization originally sited at or near a contact between mafic-ultramafic and felsic rocks. Further evaluation seems warranted.

YANNERY HILL COPPER MINE

The Yannery Hill mine (21°04'30"S, 116°55'50"E) is 2.6 km southwest of the 34 Mile camp (on the Dampier-Tom Price railway line), at the southwestern end of a narrow valley cut through the gently flexured white quartz sandstone of the Lower Proterozoic Cliff Springs Formation. Below the basal Proterozoic unconformity are outcrops of quartz-sericite schist and chlorite-quartz-sericite schist which may contain altered porphyroblasts of andalusite. The chloritic schist is the host rock of the mineralization and is commonly weakly pyritic and accordingly kaolinized in the oxidized zone immediately adjacent to the ore horizon. The major structure is a synform that plunges at 25 to 40 degrees towards 300 degrees, and which appears to have an approximately axial planar cleavage dipping steeply to the east-northeast.

The main mine workings occur in the trough of the synform, with minor openings in the steeply dipping limbs. Minor folds are common in the axial zone of the synform, and are most clearly defined by the ore horizon itself and therefore the detailed shapes of the underground openings. These minor folds range in style from upright and symmetrical, to isoclinal and recumbent and are commonly disharmonic. In general, the workings follow the plunge of the major synform and the larger productive stopes were sited in the axial regions of open, more upright minor folds (Fig. 15).

There is probably only one extensive ore horizon, which is about 50 m above the structural base of the chloritic schist (itself underlain structurally by quartz-chlorite-sericite schist). This horizon appears stratabound and consists of massive limonite, malachite, chalcocite, cuprite and other secondary copper minerals as seen in the mine. There is little quartz in the ore, and most quartz veins crosss cut the structures described and are essentially post-tectonic. The wall rocks are kaolinized or very chloritic. The ore horizon is commonly less than 1 m thick but may be 2 to 3 m thick in small shoots developed in minor fold closures. Tectonic thinning results in local gaps in the continuity of the horizon.

Intermittent copper ore production in the period 1920 to 1958 amounted to 1 132.8 t averaging 21.0 per cent copper (237.76 t copper), though production figures for 1920-1921 do not separate Yannery Hill from Whundo mine. Cupreous ore was produced more continuously from 1951 to 1968 and totalled 1 911.8 t averaging 12.87 per cent copper. Mining has been entirely in oxidized and supergene ore; the present water table is some distance below the workings. If a comparison with Whundo is valid the primary sulphide assemblage is likely to be dominated by iron sulphides.

In 1972, Gold Fields drilled three vertical percussion drillholes totalling 192 m through the Proterozoic sandstone in an effort to test the down plunge continuation of the ore horizon (Fig. 15). One drillhole (P81) was apparently successful in intersecting 200 cm of massive sulphide which assayed 2.30 per cent copper and 13.0 per cent zinc from a hand-picked sample. However the host rock was described as a hard siliceous acid to intermediate volcanic rock. Numerous small copper-zinc gossans occur in the country rocks south of the mine. Percussion drilling by Gold Fields indicated that these gossans are probably developed over iron-sulphide-dominated mineralization. Therefore, the mineralized intersection is not necessarily the ore horizon in the mine. Quartz-chlorite schist intersected in hole P81 contained anomalous copper assays up to 6600 ppm copper over a drilled width of 65 m. A systematic evaluation of the extent of this horizon

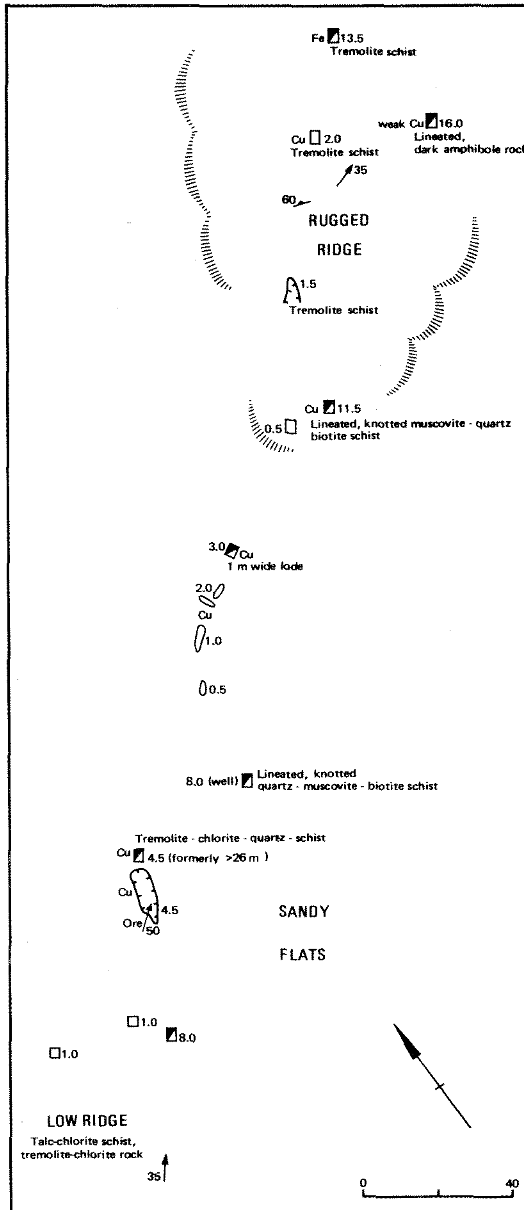

Figure 14. Surface plan of Evelyn mine

must be prefaced by detailed underground and surface structural mapping to determine the tectonic controls of the shape of mineralized sequence. As suggested by Blatchford (1913, p. 85) there are some similarities between the Yannery Hill and Whim Creek deposits, though the two obviously differ radically in size and degree and complexity of deformation. Chloritic host rocks and a spatial association with probable felsic volcanic rocks are important similarities.

CHINAMANS GRAVE PROSPECT

This prospect is 550 to 600 m northeast of Yannery mine in the same valley but on the south side of the creek. Quartz-sericite-chlorite (?) schist is exposed in an east-west costean immediately east of the track. A mineral lineation in this schist plunges at 25 degrees towards 005 degrees and a steeply west-dipping foliation is present. Some 25 m south of this costean a small gossan with pyrite boxworks occurs at the unconformity with Proterozoic sandstone. The gossan assays are low in copper and zinc, and probably represent supergene redistribution of a small mineralized lens in the schist. In the creek about 70 m north of the costean a shallow collapsed shaft and 2 pits are in a weakly copper-stained massive limonitic gossan and gossanous quartz-sericite schist. This gossan is also developed at the basal Proterozoic unconformity: percussion drilling by Gold Fields revealed a shallow northward dip of the gossan. Apart from slight surface enrichment no anomalous copper-zinc values were encountered.

WHUNDO AND WHUNDO WEST COPPER MINES

The Whundo mine (21°04′50″S, 116°55′30″E) is 3.4 km southwest of the 55 km (34 Mile) camp and 900 m southwest of Yannery Hill mine. Whundo West mine is 350 m west of Whundo mine. Low (1963) grouped the workings together as 'Whundo'. A description of the deposits is given by Reynolds and others (1975) and Roberts (1974) has compiled a detailed petrological account. A small but deep open pit was excavated on a supergene-oxidized ore shoot at Whundo in 1976.

The common country rocks (probably assignable to the Warrawoona Group) comprise:

(1) massive or foliated feldspathic metabasalt (strictly, amphibolite) with some feldspar megacrysts (relict phenocrysts) and quartz amygdales—this rock type is the most abundant in outcrop;

(2) meta-dacite or rhyodacite with some agglomerate, thoroughly recrystallized but containing pseudomorphs after bipyramidal β quartz (Roberts, 1974), and locally garnets;

(3) chlorite-muscovite-quartz schist of variable composition (some very chloritic, some muscovite-rich) with local porphyroblastic andalusite—pyritic and kaolinized or ferruginized in the oxidized zone;

(4) crosscutting and concordant metagabbros and dolerite dykes, and,

(5) an essentially post-regional metamorphism biotite granodiorite which intrudes all the above rocks except some dolerite dykes.

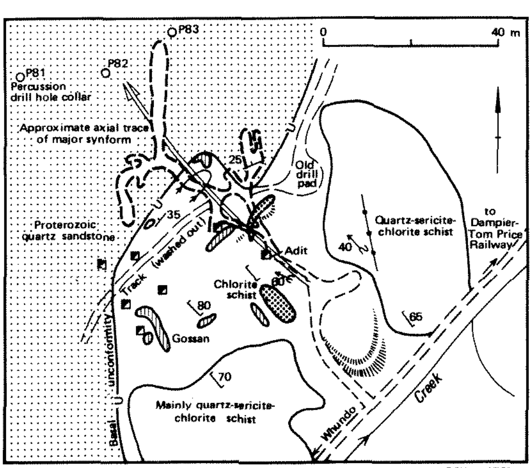

Figure 15. Surface geology and general extent of underground workings at Yannery Hill mine

These rocks have undergone regional metamorphism to greenschist-amphibolite transition facies which is overprinted by hornblende hornfels facies contact metamorphism probably related to the biotite granodiorite stock (Roberts, 1974). The rocks are accordingly thoroughly recrystallized and many (including the sulphide mineralization) contain tectonic fabrics (Roberts, 1974). The ore shoots occur within the schist unit at or just above a contact between mafic (below) and felsic metavolcanic rocks. On a regional scale the lithology defines a complex major synformal structure plunging moderately to the north. In outcrop the schistosity is parallel to rock boundaries. Both this schistosity and the ore shoots are folded (e.g. footwall schist and gossan at Whundo West) by small upright folds plunging moderately northwestwards or northwards, which contain a coaxial mineral lineation that parallels the plunge of the ore shoots. North-trending faults complicate this picture. Discontinuous goethite-hematite gossans trace out a sinuous line of outcrops some 500 m long which appears to be approximately the same horizon (Reynolds and others, 1975). The ore shoots reach a maximum thickness of 20 m but are commonly 1 to 5 m thick. They have a restricted strike length and down-plunge dimension of less than 150 m each. Three diamond drillholes totalling 1 089 m were drilled by Gold Fields in 1972, 350 to 400 m north of the Whundo-Whundo West workings. Chloritic schist without significant mineralization was encountered in all holes.

All exploited mineralization is in the oxidized zone which consists of malachite, azurite and cuprite grading down into a supergene assemblage of abundant sooty chalcocite plus marcasite, pyrite, neodigenite, sphalerite, covellite and chalcopyrite with accessory native copper. The enriched zone may extend down to 49 to 55 m below surface, though primary sulphides are present from 35 m downwards (Reynolds and others, 1975). The primary sulphide assemblage is pyrite, pyrrhotite, sphalerite, chalcopyrite and minor arsenopyrite, accompanied by magnetite. Roberts (1974) recognized three types of primary massive sulphide ore as follows (in order of decreasing abundance):

(a) fine-grained to medium-grained pyrite-sphalerite with subordinate pyrrhotite and chalcopyrite—sphalerite and chalcopyrite may form layers a few millimetres thick;

(b) medium-grained to coarse-grained pyrite and pyrrhotite (85 to 95 per cent) with minor or accessory sphalerite and chalcopyrite;

(c) pyrite plus chalcopyrite and sphalerite in layers, veins and stringers up to a few centimetres thick, in the wall-rock chloritic schist.

At Whundo West massive sulphide type (b), which is essentially barren, overlies type (a). Type (a) has grades in the range 2 to 3 per cent copper and 2 to 5 per cent zinc, though if the sulphide ore was mined effective grades might be only about 2 per cent copper and 1.3 per cent zinc. In 1976 Whim Creek Consolidated estimated an indicated resource (based on 30 diamond drillholes) of about 2 Mt at these lower grades for the Whundo and Whundo West shoots. The recently extracted chalcocite ore at Whundo amounted to 6 200 t averaging 27 per cent copper. In 1977 the company indicated that 48 000 t of 7.4 per cent copper at Whundo West might be mined. Previous copper ore production totalled 1 158 t averaging 20.38 per cent copper (236 t copper) whereas cupreous ore production has amounted to 1 056 t averaging 9.83 per cent copper. Details of the old copper workings are given in Low (1963, p. 80).

Both Reynolds and others (1975) and Roberts (1974) concluded that the mineralization is of volcanogenic origin though subsequently somewhat modified by metamorphism and deformation. The high selenium contents of sulphides and the low nickel:cobalt ratios in pyrite determined by Roberts (1974) suggest that the sulphur and pyrite are of magmatic origin. Roberts noted that the chlorite schist commonly enclosing mineralization grades into 'chloritized metavolcanic rock' and suggested that the schist was a product of wall-rock alteration involving the introduction of iron, magnesium and aluminium in particular. The latter element could also account for the occurrence of andalusite in some of the wall rocks. If the host chlorite schist is largely a product of wall-rock alteration, the apparent abundance of this rock type in areas lacking mineralization, and the low mean content of copper (20 ppm) and zinc (100 ppm) in the wall rocks to the ore shoots are surprising.

COPPER MINERALIZATION ASSOCIATED WITH FRACTURE OR QUARTZ VEIN STOCKWORKS (TYPE D)

INTRODUCTION

Deposits of this type have been found only in the East Pilbara and the majority occur in or adjacent to major domal structures. The host rocks are largely metavolcanic and/or are metamorphosed high-level porphyritic felsic hypabyssal intrusives of various shapes. The sulphide mineralization may be present as disseminations in the host, disseminations in quartz or porphyry veins, or as thin veinlets and fracture coatings. Pyrite is the major sulphide with minor chalcopyrite and lesser molybdenite being commonly present. Various types of 'alteration' affect the host rocks including silicification, kaolinization (argillization, sericitization), chloritization, epidotization and carbonation. Of these, silicification can commonly be regarded as hydrothermal in origin because it is spatially related to quartz veins in many examples. The chloritization appears to be of multiple origin perhaps being metasomatic in part, but of retrograde metamorphic generation elsewhere. Kaolinization is commonest and is probably largely a by-product of the meteoric alteration of disseminated sulphides. Thus although subsurface information is limited and regional metamorphism has partly changed the character of the deposits, some features of some deposits may be shared with the porphyry copper type deposits of younger terrains. However, the similarities (e.g. stockworks, association of copper and molybdenum, presence of felsic hypabyssal intrusives) are probably equalled by the differences (e.g. lack of zoned hydrothermal alteration, the dominance of vein quartz in stockworks, the lack of an island arc type of geotectonic setting). Perhaps these deposits can be regarded as a primitive, Archaean porphyry copper type of mineralization.

McPHEE DOME AREA

Three similar copper-molybdenum occurrences are known from the McPhee Dome, a major oval structure centred about 35 km north-northeast of Nullagine. Felsic metavolcanic rocks are a major rock type in the core of the dome, which is also typified by variable but low to gentle dips and small, irregular stocks of porphyritic biotite granite-adamellite-granodiorite.

The McPhee Creek East prospect (21°37′40″S, 120°16′00″E) is on the northeastern flank of a granitoid intrusion about 1 km in diameter. This intrusion consists of biotite granitoid containing rounded quartz phenocrysts, and quartz-feldspar porphyry. Some phases are leucocratic and very fine grained. Emplacement may have taken place at a high, perhaps subvolcanic, crustal level. A stockwork of fractures and quartz veins is present on the northern flank of the intrusion in a suite of metadolerite, metagabbro and granophyric mafic rocks. The host rocks to this stockwork (area about 1 km^2) are generally kaolinized and are chloritized marginal to or in the fractures. The fractures may contain limonite, vein quartz, epidote and rare secondary copper minerals. In 1973, Anglo American drilled two diamond drillholes totalling 334 m to test the stockwork area, which soil and surface rock geochemical surveys had shown to be anomalous in copper and molybdenum. Results were negative with less than 0.5 per cent disseminated iron-copper-molybdenum sulphides present in general. The mineralization was largely confined to thin quartz veins. The host rock alteration is probably mainly of meteoric origin.

The Gobbos prospect is 10 km north-northeast of McPhee Creek East prospect, but in contrast the rocks are generally fresh in outcrop. A petrologically similar but larger granitoid stock (also containing rounded quartz phenocrysts) has intruded felsic metavolcanic rocks and pillowed variolitic metabasalts on the northern flank of the McPhee Dome. Thin quartz and quartz-feldspar porphyry veins form stockworks principally in the contact zone but also sporadically in the granitoid. Disseminations and coatings of fresh chalcopyrite and molybdenite can be seen in fractures and veins in exposures in the incised creek draining north-northeastwards.

The Lightning Ridge prospect (21°29′50″S, 120°17′00″E) is 15 km north-northeast of McPhee Creek East prospect on the northeastern periphery of the largest granitoid stock intruding the northern flank of the McPhee Dome. The mineralized quartz veins are in volcanic or hypabyssal porphyry emplaced in the country rocks. The porphyry may be sericitized, silicified or chloritized. A programme of seventeen shallow percussion drillholes put down by Conwest in 1967 intersected up to 1.1 per cent copper over 30 m and about 0.1 per cent molybdenum over 12 m. A single diamond drillhole sunk by Newmont in 1971 encountered sparse disseminations (less than 1 per cent) of pyrite and chalcopyrite and local fracture coatings of molybdenite.

COPPIN GAP PROSPECT

The Coppin Gap prospect (20°53′20″S, 120°06′30″E) is 1.5 km southwest of Coppin Gap, which is a gorge breaching a thick ridge-forming unit of banded iron-formation that occurs immediately north of the prospect (Fig. 16). The prospect is in the centre of a narrow east striking belt of felsic to ultramafic metavolcanic rocks, chert and metasedimentary rocks that dip northwards at about 65 degrees. To the south, a northern lobe of the Mount Edgar batholith has stoped into the belt, and marginally this intrusive is a massive, high-level biotite adamellite with round quartz phenocrysts, quartz veinlets, and accessory pyrite and chalcopyrite. The following account is based on the author's field observations, and on data obtained by Anglo American and Esso during exploration programmes carried out on the prospect.

Variably carbonated and silicified metabasalt and subordinate dacite-rhyolite are the main host rocks. The metabasalt contains disseminated chalcopyrite and iron sulphides, particularly in flow top breccias, and assays in the range 1 000 to 2 000 ppm copper. The dacite-rhyolite contains only a trace of chalcopyrite, sphalerite and iron sulphides and generally contains less than 100 ppm copper. Minor iron and nickel sulphides are present in intrusive and spinifex-textured ultramafic rocks occupying a postulated major strike fault between the banded iron formation to the north and the volcanic sequence to the south.

The volcanic sequence is intruded by several sub-concordant, lensoid to tabular bodies of dacite porphyry, characterized by brecciated and silicified contact zones which also contain mafic to ultramafic hornfelsic rocks (e.g. diopside-hornblende-tremolite). These silicified zones are capped by Tertiary siliceous mantles, and thus stand up as broken, rugged ridges. The youngest intrusive igneous phase is a fine-grained to medium-grained granodiorite to quartz-oligoclase porphyry, which forms flat-lying and rare dyke-like bodies, and is poorly represented at the present level of erosion. The granodiorite contains disseminated chalcopyrite and iron sulphides, and commonly averages 1 000 ppm or more copper.

A multiple phase stockwork of quartz-carbonate veins (with or without chlorite, potash feldspar and biotite), carrying up to 2 per cent chalcopyrite, as well as molybdenite, pyrite, pyrrhotite, and rare sphalerite and scheelite, has been emplaced in the volcanic sequence over an area of some 1 to 2 km^2. The stockwork is best developed in the silicified contact zones of the dacite porphyry, and contains the better copper-molybdenum mineralization where intrusive bodes of granodiorite are also present. Further wall rock silicification along with sericitization, carbonatization and the rarer metasomatic development of potash feldspar, biotite or chlorite, are hydrothermal alteration features associated with the stockwork emplacement. The stockwork was evidently emplaced after deformation and regional metamorphism, but the presence in some veins of intergrown coarse flakes of randomly oriented chlorite or biotite with iron-copper sulphides, suggests recrystallization perhaps under the influence of a later thermal event.

Showings of secondary copper minerals are rare in outcrop. In the period 1970-1973 Anglo American carried out a limited diamond drilling programme, which encountered low-grade iron sulphide-chalcopyrite-molybdenite mineralization in silicified porphyry and microgranodiorite. The best intersection was 75.6 m assaying 0.23 per cent copper and 0.13 per cent molybdenum. A more detailed investigation by Esso commenced in 1974, and to date twenty-three vertical diamond drillholes, spaced on a 250 m triangular grid, have been bored. Evaluation by that company is continuing.

BREENS COPPER MINE

The Breens (North Pole, Peary Reward) mine (21°06′00″S, 119°21′50″E) is 1.7 km north-northwest of the old North Pole gold battery, on the north-western flank of the North Pole Dome (Hickman, 1975a), about 1 km west of the granitoid stock emplaced in the core of the dome. Production was first recorded in 1911 when 9.50 t of copper ore (1.41 t copper) was raised. In 1955-1956 289.6 t of cupreous ore averaging 12.16 per cent copper was raised from a shaft servicing shallow stopes to the north and south. In 1957 43.52 t of copper ore (4.86 t copper) was produced.

A sequence of mixed, mafic to felsic metavolcanic rocks dips moderately northwestwards, and is intruded by sills and dykes of metagabbro or metadolerite and by veins or dykes of quartz and quartz-feldspar porphyry. The mineralized area occurs near the base of the sequence in a northeast-striking, 500 m wide belt of variably bleached (kaolinized), silicified and brecciated mafic to felsic metavolcanic and volcaniclastic rocks dipping northwestwards. A stockwork of thin (few centimetres) quartz-limonite veins with sporadic, weak malachite stains, occurs throughout this belt but is less well developed northwestwards.

The most prominent features in the belt are two moderately east-dipping or south-dipping, strongly silicified breccia zones. These form rugged sinuous outcrops of fractured, amorphous chert and fine-grained quartz reaching several tens of metres in thickness. Concordant, weakly limonitic areas, rarely copper-stained, are found in these zones. Cherts filling irregular, steep fractures in the altered country rocks are found west of these tabular, silicified zones (Hickman, 1973). The solitary shaft of the mine (water at 11.5 m, bottom at 14 m) has been sunk immediately east of a small copper-stained, siliceous gossan 5 to 20 cm thick, within the east-dipping silicified breccia zones where they appear to merge as one zone. Exposed in the creek immediately northwest of the shaft and structurally below the silicified zone, is a limonite-quartz vein stockwork in bleached metabasalt.

From 1968 to 1971, Planet conducted exploration in the area of the mine under an option agreement with J. A. Johnston the holder of MC 1095. In 1968, eight vertical percussion drillholes 12.8 to 42 m deep were sunk close to the shaft. The best intersection of 32 m assaying 2.55 per cent copper (10.1 to 42.1 m depth) came from drillhole D7, collared in the creek 12 m north of the shaft. This drillhole appears to have penetrated the east-dipping silicified breccia zone including two lenticular sections of massive sulphides (pyrite, chalcopyrite and chalcocite plus minor covellite, neodigenite and native copper) in quartz gangue at 22 to 27 m and 30 to 35 m depths. A diamond drillhole (DDH1) collared 7 m west of D7 intersected only one massive sulphide lens, and assayed 1.92 per cent copper and 22.6 g/t silver over 35.1 m. In 1970, twenty-four percussion drillholes were drilled to 11 to 35 m depths to test the disseminated (stockwork) mineralization in the altered country rocks. The results were disappointing, and further drilling only served to indicate that the shallow mineralization of possible economic interest was confined to the east-dipping, silicified breccia zone.

Some rock units in the volcanic sequence contain disseminated pyrite (up to 5 per cent) in addition to the quartz veins containing chalcopyrite, pyrite and rarely traces of molybdenite. Some quartz veins are auriferous; several old, gold workings occur northwest of Breens and copper is associated with some. The source of the widespread stockwork mineralization has not been determined. It appears to be post-dated by the silicified breccia zones, and may be related to the

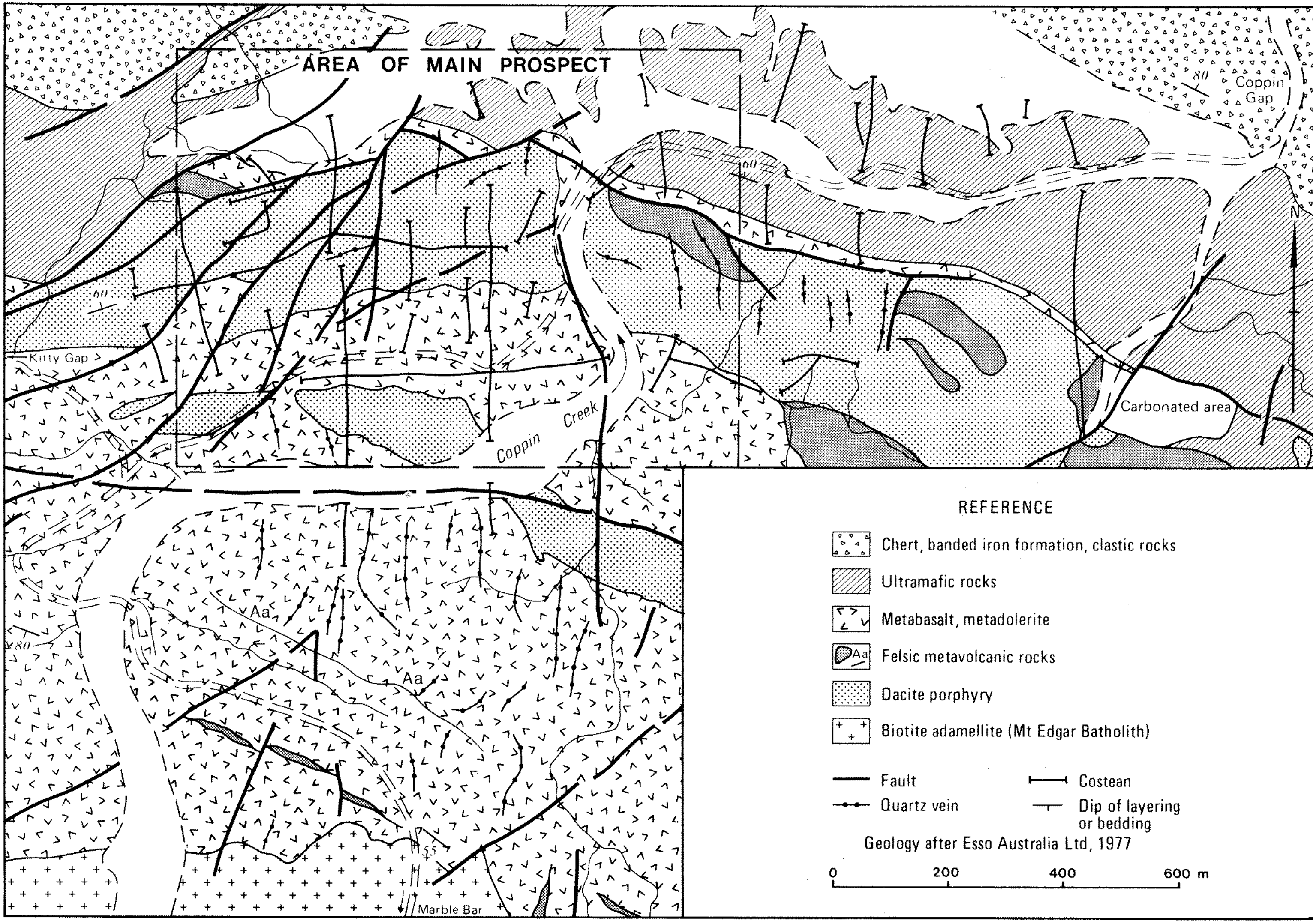

Figure 16. Geological map of the Coppin Gap copper-molybdenum prospect

pervasive kaolinization and silification both of which are evidently of hydrothermal origin. Furthermore minor occurrences of stratabound pyritic mineralization containing small amounts of zinc and copper sulphides are known from the general area and also from the east flank of the North Pole Dome.

The area has a complex history of mineralization including stratabound, stockwork and tectonically located cupriferous deposits. In the Breens area the nature of the stockwork mineralization at depth seems worthy of further appraisal.

COPPER HILLS COPPER MINE

The Copper Hills mine (21°39′30″S, 119°58′40″E) is situated on the southeastern flank of the Corunna Downs batholith in north-northeast-striking mafic to felsic metavolcanic rocks (Warrawoona Group) of the Kelly Belt (Hickman, 1975a). From discovery in 1952, until closure in 1963, the mine (GML314L) produced 49.22 t of copper ore and concentrates averaging 35.08 per cent copper (17.27 t copper) and 15 455.67 t of cupreous ore and concentrates averaging 12.68 per cent copper. The bulk of the copper ore probably came from Copper Hills West as production from the two centres was reported together. A small amount of cement copper was produced from an in situ leaching plant operated from 1969 to 1972 by S. H. Stubbs.

The mine is located near the northern end of a 28-km-long belt of coarse-grained, quartz-feldspar-biotite porphyry with a dark green to black groundmass, called the 'Copper Hills Porphyry' by Noldart and Wyatt (1962) and re-defined in part as the Boobina Porphyry by Hickman and Lipple (1975). The porphyritic rocks at Copper Hills itself are unlike this distinctive porphyry, being finer grained, pale green-grey when fresh, and containing corroded quartz and/or feldspar (albite or orthoclase) phenocrysts in a matrix of quartz, sericite and feldspar plus minor chlorite, carbonate, pyrite and chalcopyrite. Hickman and Lipple (1975) mapped some of these rocks as felsic tuff and noted the presence of agglomerate and shards. Examination of drill core reveals sections of porphyry which are chloritized and epidotized. The mine workings are in the saddle of an isolated, north-northeast striking, rugged rocky ridge composed of rusty brown weathering, thoroughly fractured and sheared quartz-feldspar porphyry. Zones of chloritized porphyry are darker and less well exposed. All rocks in outcrop are deeply weathered and are kaolinized or sericitized. This ridge may coincide with the main extent of the porphyry as chert and felsic metavolcanic rocks crop out to the north, west and south of the ridge. Common fracture sets developed are : (i) 320 to 340 degrees, (ii) 000 to 030 degrees, (iii) 060 degrees, and (iv) 270 to 285 degrees. Dips are steeply to the north or west.

Except in the open cuts (Fig. 17) there is very little sign of copper mineralization at the surface probably because of strong leaching. Low (1963, p. 32) reports that the leached areas occur above and adjacent to supergene ore concentrations. The extent of the workings indicates a mineralized area 150 m long and 50 m wide. Masses of porphyry several metres in diameter in the open cuts are surrounded by fractures which carry green malachite staining. There appears to be very little copper staining in the porphyry itself. Judging from the drill core, widely disseminated pyrite-chalcopyrite mineralization (Appendix 1) has been irregularly concentrated by supergene processes into the fractures, although thin lenses and veinlets of primary sulphides do occur. The supergene minerals are reported to be chalcocite and bornite. The main underground workings are at the southern end (Fig. 17) and consist of levels at 30.5 and 42.7 m depths, served by an adit driven from the west. Most mining was carried out from the 30.5 m level in carbonate and supergene sulphide ore including a stope through to the surface.

In 1960-1961 twenty-four short, horizontal and depressed diamond drillholes were bored by S.H. Stubbs from various openings at the 30.5 m level into supergene mineralization in an effort to plan further development. Most assays were in the range 0.3 to 1.5 per cent copper over 30 to 50 m, with exceptional values of about 20 per cent copper over 3 m, and about 4 per cent copper over 7.6 m. The copper values in the primary zone probably average considerably less than 1 per cent copper, as indicated by two inclined diamond drillholes bored by New Consolidated Goldfields (Aust) Pty Ltd in 1957 to depths of 119 m and 155 m below the ridge at each end of the mineralized zone (Low, 1963, p. 32). Two inclined diamond drillholes were sunk in 1966 by Metals Ex to test for downward extensions to the mineralization. One hole passed out of leached rock at a downhole depth of 61 m, but intersections were generally less than 1 per cent. In the same programme five other diamond drillholes were bored in bleached rocks southwest and northeast of the mine with the discovery of only disseminated pyrite with traces of chalcopyrite. Similarly disappointing results were obtained from three diamond drillholes drilled in the mine area by Newmont in 1970-1971.

The primary mineralization is disseminated in a porphyritic felsic igneous (perhaps subvolcanic) host and appears to be of magmatic-hydrothermal origin. It stands apart from the other deposits described in this section because a quartz vein stockwork is absent and the mineralization appears to lack molybdenum. The pervasive kaolinitic-sericitic alteration appears to be meteoric in origin. The bulk of the carbonate ore and some supergene ore has been extracted. Indicated grades of primary sulphides are too poor for a body of this size, although this mineralization could improve below the shallow depths tested so far.

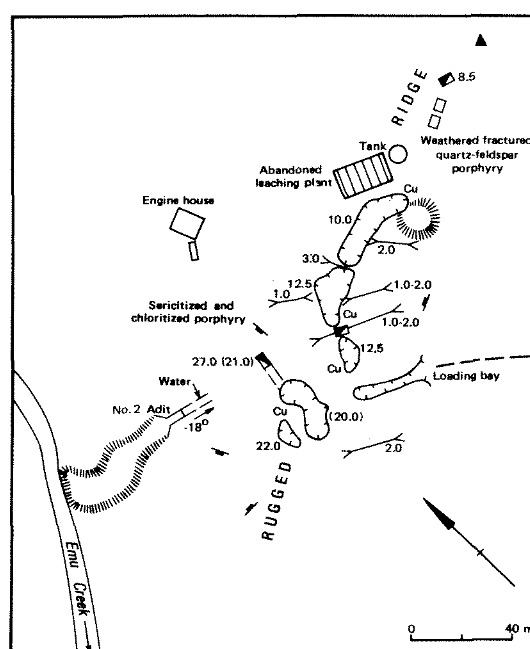

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Figure 17. Surface plan of Copper Hills copper mine

CUPRIFEROUS QUARTZ VEINS AND SHEARS (TYPE C)

FELSIC METAVOLCANIC AND HYPABYSSAL HOST ROCKS

COPPER HILLS WEST MINE

The Copper Hills West mine (21°39′30″S, 119°58′10″E) is 1.2 km west-northwest of Copper Hills mine. The only recorded production is 2.84 t of cupreous ore averaging 13.17 per cent copper raised in 1956, on P.A. 746L. The extent of the workings (Fig. 18) suggests that considerably more mineralized material than this has been extracted. In 1956, 422.95 t of copper ore averaging 24.52 per cent copper (103.70 t copper) was raised by MC 96L, and probably came from the Copper Hills West mine. The host rock is chloritized and kaolinized, brecciated or strongly fractured feldspar porphyry. Some variants are aphyric and siliceous, and may be recrystallized chert, rhyolite or volcanic breccia. Two main shears are mineralized (Fig. 18), and contain lenses of copper-stained goethite rarely up to 20 cm thick in vein quartz. A weak stockwork of thin quartz-limonite veinlets occurs in bleached country rock marginal to the main shears. Malachite, chrysocolla and rare azurite are present sporadically in the shears and stockwork.

Some 500 to 800 m northeast of the mine, two chert bands crop out within poorly exposed chloritized porphyry and acid breccia. In 1969-1970 Hawkstone prospected this area for stratabound massive copper-zinc sulphides. The best result obtained from seven inclined diamond and percussion drillholes totalling 724 m was an intersection of 1.22 m assaying 0.73 per cent copper, from scattered chalcopyrite blebs in a rhyolite breccia. Minor zinc mineralization was also found.

COPPER HILLS SOUTH MINE

These workings (21°40′40″S, 119°57′50″E) are 4 km south-southwest of Copper Hills mine in fractured and reddened, medium-grained to coarse-grained quartz feldspar porphyry with a dark green chloritic-saussuritic matrix (Boobina Porphyry). This porphyry becomes more fractured north-northeastwards. Two shallow shafts 140 m apart and a pit have been sunk on silicified and disseminated limonite-malachite-azurite-bearing shears striking 300 to 310 degrees and dipping 65 to 75 degrees to the southwest. Production is unrecorded but may have amounted to a few tonnes. In 1957 New Consolidated Goldfields drilled two inclined diamond drillholes some 100 m apart into the mineralized zone. Veinlets and disseminations of pyrite and chalcopyrite were encountered in and between two thin quartz veins. The best result was 5.31 per cent copper over 0.3 m drilled width. The mineralization appears to be of no economic importance.

KELLYS COPPER MINE AND PROSPECTS

Workings at Kellys (Mondana) mine (21°47′30″S, 119°52′20″E) occur sporadically over 600 m in a north-northwest-striking faulted contact zone at the south-western termination of the Boobina Porphyry. The country rocks to the west are sheared felsic ?tuffs in the north and metabasalts in the south.

The main workings are in the north and between 1955 and 1970 609.69 t of cupreous ore averaging 19.47 per cent copper were produced by various parties. These northern workings are on the south slope of a ridge and consist of a collapsed open stope 5 to 10 m deep, 1 to 3 m wide and 25 m long which trends 004 degrees and dips east at 85 degrees. A shaft 24.6 m deep is at the northern end of the stope and another 18.5 m deep is sited at the southern end. The host rock is a highly fractured and brecciated, chloritic quartz-feldspar porphyry. Some of the porphyry contains mafic fragments which may be metabasalt included in the intrusive contact zone of the Boobina Porphyry. The stope is opened in a shear zone carrying vein quartz and copper-stained limonitic veins and lenses up to several tens of centimetres thick. Malachite, azurite, cuprite, and chrysocolla occur in the oxidized zone with bornite and chalcocite present as supergene sulphides at the base. The primary sulphides are pyrite and chalcopyrite in a quartz, sericite, chlorite gangue. The richest mineralization is in short shears, but disseminated sulphides are marginally present in the host rocks.

Percussion drilling by Cominco and Hawkstone in 1968-1969 failed to find any encouraging copper values in the oxidized zone (the best intersection was 12.2 m of about 2 per cent copper) or any evidence for a substantial body of disseminated mineralization. High-grade intersections were restricted to narrow shears and tension gashes.

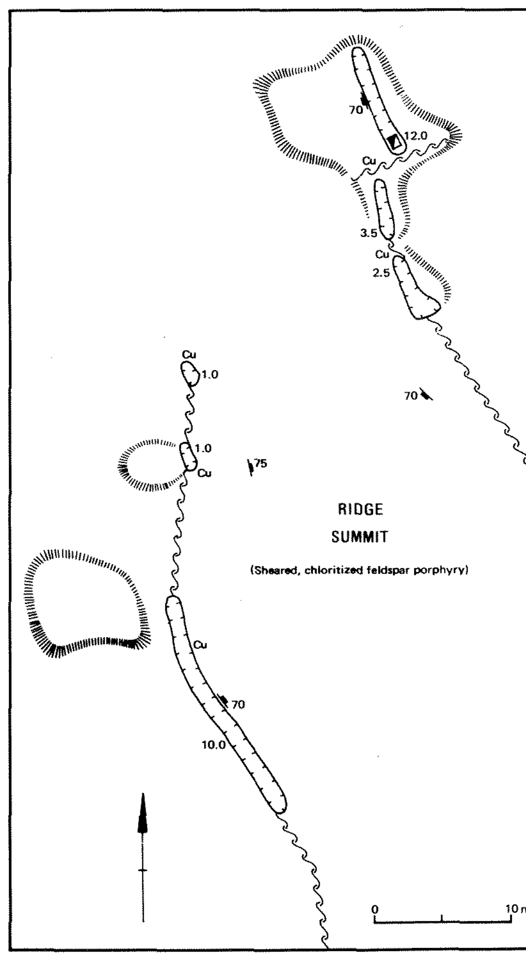


Figure 18. Surface plan of Copper Hills West workings

Small prospect pits, shafts and costeans in the same silicified, brecciated, fractured and quartz-veined contact zone occur 200 m and 400 m south-southeast of the main mine opening. Thin weakly mineralized shears trend 310 to 340 degrees and are vertical or dip steeply east. An inclined percussion hole bored from the east-northeast through this area encountered 6.1 m assaying 0.25 per cent copper and 7.6 m assaying 1 per cent copper in the oxidized zone. Other percussion drilling here indicated a lack of strike persistence of such mineralization. Hawkstone also attempted to locate large low-grade bodies of copper mineralization in fractured pillowed metabasalt overlying chert, in areas 600 m southwest and 1 500 m south-southeast of the main mine. In the latter area very low-grade (0.3 to 0.6 per cent copper) iron-copper sulphides were found in only two out of seven percussion holes drilled.

Scattered pits, shafts and small excavations occur north of the main mine for about 300 m in shears in fractured porphyry and felsic metavolcanic rocks. One of these workings (PA 857) produced 18.44 t of cupreous ore assaying 10.35 per cent copper in 1964.

The surface expression of all mineralization in the area is weak and of very limited extent. Although there has not been adequate testing at depth, the exploited mineralization seems to represent the mobilization of patchy, copper-poor, disseminated iron sulphides into structural sites. The existence at depth of higher grade disseminated ore bodies of any size seems unlikely from current information.

RYANS COPPER PROSPECT

This prospect (21°48′50″S, 119°51′00″E) is 3.7 km southwest of Kellys mine. It occurs just north of where a 1 to 3 m wide silicified shear zone, striking 340 to 350 degrees and dipping 65 to 75 degrees to the west, cuts an east-northeast-striking, steeply south-dipping, massive chert ridge 15 to 20 m wide. Strongly fractured and silicified metabasalt crops out south of the chert (which may be a tectonic infilling) and felsic agglomerate is present to the north. The shear zone contains 1 cm thick veinlets of copper carbonates, and lenses or veins up to 20 cm thick of copper-stained limonite occur in the adjacent metabasalt and agglomerate. A small prospecting pit has been sunk on one such lens. A diamond drillhole put down by Hawkstone intersected 1.5 m assaying 2.9 per cent copper at the chert-agglomerate contact in the sulphide zone. Disseminated pyrite was found in cherts and felsic pyroclastic rocks to the east and east-northeast of Ryans prospect.

It is unlikely that any mineralization in the area could prove to be of economic interest.

MARBLE BAR SOUTH COPPER-GOLD MINE

This small mine (21°14′10″S, 119°46′30″E) is 7.6 km at 155 degrees from Marble Bar, and 1.5 km from the southwestern margin of the Mount Edgar Batholith. The country rocks are cleaved, pyritic quartz-sericite rocks (felsic meta-tuffs and lapilli tuffs) of the Warrawoona Group, which dip steeply to the southwest. The mineralization consists of quartz-goethite (largely after pyrite) veins striking northeast and dipping steeply northwest (Fig. 19). Stains and fracture coatings of chrysocolla are abundant, azurite and malachite are rarer.

The principal mineralized vein has been worked for a short distance into the hillside (Fig. 19) in a 1 m wide zone of weak cupriferous-ferruginous dissemination and veinlets. Recorded production is 11.20 t of copper ore (1.67 t copper) in 1911 (ML 185), 57.30 t of cupreous ore (9.4 per cent copper) in 1955 (PA 2474) and 40.96 t of cupreous ore (19.4 per cent copper) in 1969-1970 (PA 2874 and MC 1614). The copper ore contained silver (2027 g/t) and gold (5.13 g/t). Newmont drilled four diamond drillholes in 1970 and encountered disseminated pyrite and low-grade zinc mineralization over intervals of 60 to 120 m.

METASEDIMENTARY HOST ROCKS

MIDDLE CREEK GOLD MINING CENTRE

This centre (21°52′40″S, 120°17′00″E) is 18 km east of Nullagine in pelitic schist and phyllite of the Mosquito Creek Formation (upper Gorge Creek Group). Minor copper production has been reported from PA 687 (7.62 t of copper ore containing 0.41 t copper) in 1951 and PA 809 (4.04 t of cupreous ore averaging 8.88 per cent copper) in 1961. These tenements may coincide.

SALGASH COPPER PROSPECT

This prospect (21°16′00″S, 119°49′30″E) is 13 km southeast of Marble Bar and consists of a series of small disseminated and veiniform copper occurrences principally found along an east-southeast trending strike fault. Copper minerals accompany gold in old workings located in the fault. This fault is within psammite and quartz-chlorite schist just south of a contact with serpentine and talc-carbonate-chlorite schist to the north. Disseminated malachite and chalcocite occur in the quartz-chlorite schist and in quartz veins. Chalcocite veins have also been found in talc schist. Percussion drilling carried out by Hawkstone in the early 1970's showed that copper values decreased with depth, the best result being 1.5 m of 0.95 per cent copper in the oxidized zone, west of the old gold workings.

ABYDOS NORTHEAST AREA

This area is located close to a northeastern lobe of the Yule Batholith. At the Abydos Northeast prospect (21°20′00″S, 119°00′10″E) malachite and limonite disseminations occur over a 50 m strike length and 1 m width in siliceous metasedimentary rocks striking north. Assays of two samples of gossanous material returned 15 000 ppm and 980 ppm copper. Some 2.5 km to the southeast of this prospect 10.43 t of cupreous ore assaying 8.77 per cent copper were extracted in 1963 (MC 633) from a minor copper occurrence in ultramafic rocks. There are further copper occurrences in ultramafic rocks 4 km to the east and northeast of the latter prospect.

COFFIN BORE OCCURRENCE

About 100 m north of the prospector's camp at Coffin Bore (21°04′30″S, 118°53′00″E) there is a 2 m deep pit in a medium-grained, recrystallized quartz vein. Small patches of copper-stained limonite are disseminated in the east-trending vein. Float in the area is of metasedimentary and metavolcanic rocks.

STANNUM COPPER PROSPECTS

These small prospects are in the southern part of the Wodgina Belt, a large south-southwest striking remnant of supracrustal rocks within the northern part of the Yule Batholith.

Stannum West (21°14′40″S, 118°36′40″E) is the main prospect and is located 8.6 km at 230 degrees from Mount Tinstone, about 500 m from the western margin of the Wodgina Belt. Here thin veinlets and sparse disseminations of goethite-malachite-chrysocolla occur sporadically in a south-southwest striking 200 m long and up to 10 m wide zone of mixed quartz-feldspar-muscovite-chlorite schist and amphibolite. Diopsidic amphibolite and ultramafic rocks occur to the west and semi-pelitic to psammitic schist is present to the east. A layer parallel, sub-vertical metamorphic foliation is accompanied by a mineral lineation plunging north-northeast at 50 to 65 degrees. Four shallow pits have been excavated in the mineralized zone and 3.71 t of cupreous ore assaying 6.25 per cent copper was produced in 1963 (PA 2687). Diamond drilling by Pancontinental Mining Ltd in 1974 encountered pyrrhotite, pyrite and minor chalcopyrite as veinlets and disseminations parallel to the schistosity. Only one out of the three drillholes intersected primary sulphides which assayed 0.17 per cent copper over 6 m. In probable supergene mineralization 10 m of 0.56 per cent copper were intersected. The prospect appears to be of no economic importance.

The Stannum Northeast prospect (21°14′00″S, 118°36′20″E) is 3 km east-northeast of Stannum West in the core of the Wodgina Belt. At a contact between recrystallized chert and psammite to the east and micaceous schist to the west, a 2-m-deep pit reveals iron-stained kaolinized rock with rare feeble copper staining.

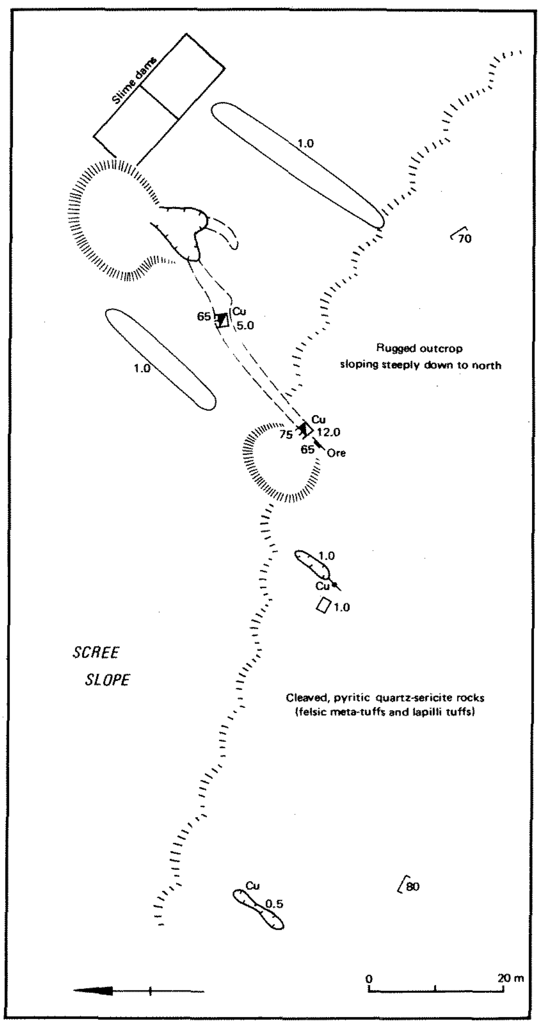


Figure 19. Surface plan of Marble Bar South mine

OTHER OCCURRENCES

Only the Devil Creek occurrence has been inspected. At the Pilbara gold mining centre (21°14′30″S, 118°17′00″E) copper-stained schists are reported to occur adjacent to a banded chert ridge striking east-northeast. Copper minerals are also found in quartz veins here.

The Quamby and Kopje workings (21°03′50″S, 117°50′50″E) are about 3.5 km north of Evelyn copper mine on a lenticular cupriferous quartz vein up to 1 m wide and traceable for 40 m. The country rocks are probably mixed, medium-grade metasedimentary and mafic-ultramafic rocks, like those present in the Evelyn area. In 1907 15.24 t of oxidized copper ore (4.11 t copper) were raised (ML 103). In 1952 44.59 t of cupreous ore averaging 6.83 per cent copper was produced (PA 234).

The Devil Creek occurrence (20°58′20″S, 116°21′30″E) is near the core of a narrow, southwest-striking supracrustal belt in the West Pilbara. A 3-m-deep pit has been sunk on a small lens of copper-stained limonite and vein quartz in grey tuffaceous (?) slate immediately west of a silicified ferruginous chert ridge. Large quartz blows occur along strike from the mineralization, which probably occupies a strike-faulted zone.

MAFIC-ULTRAMAFIC IGNEOUS HOST ROCKS

CALLAWA PROSPECT

Callawa prospect (20°44′00″S, 120°26′10″E) is in mafic rocks 8 km southwest of Callawa homestead 1.5 km north of the northern margin of the Warrawagine Batholith. Amphibole-plagioclase schist strikes north-northeast and contains a sporadically cupriferous quartz vein, emplaced more or less parallel to the strike. Some shallow gouging has been done but no production is recorded.

YARRIE SOUTH OCCURRENCES

At the northern (20°44′00″S, 120°11′30″E) of these two occurrences in foliated ultramafic rocks on the east side of the Muccan Batholith, a limonitic quartz vein assayed 10.5 per cent copper, 0.5 ppm gold and 6.3 ppm silver from a surface sample. A similar occurrence 1.5 km to the southwest has been worked in a small way for gold. A surface sample of limonitic material assayed 2.56 per cent zinc, 1 400 ppm copper, 2.4 ppm gold and 83 ppm silver.

LIONEL COPPER DEPOSITS

These workings (21°39′40″S, 120°06′50″E) are 25 km north of Nullagine on the southwestern flank of the McPhee Dome. The country rocks are weathered (ferruginized and/or bleached) metagabbros striking north-northwest and probably dipping steeply west. Cupreous ore was produced from the area from 1954-1956 and 1962-1964 and amounted to 372.10 t averaging 15.47 per cent copper. Total copper ore production is 39.71 t averaging 25.71 per cent copper. The workings extend for 350 m in an east-northeast direction, but the main openings are in the centre and at the eastern end (Fig. 20). In the central group of workings, quartz-limonite-malachite veins, veinlets and lenses are from a few millimetres to 70 cm in thickness, commonly strike between 060 and 075 degrees, and dip moderately to steeply northwards. In contrast, the eastern group contains bunches of chalcopyrite and pyrite perhaps up to 30 to 40 cm in size, in massive, coarse-grained calcite veins. Chalcopyrite was encountered at a depth of about 12 m. Quartz-limonite-azurite-malachite veinlets occur marginally in the metagabbro, which is at its freshest here. Mineralization is thin and feebly developed elsewhere.

EMU CREEK EAST MINE

This small mine (21°37′40″S, 119°59′10″E) is 3.5 km north-northeast of Copper Hills mine. A siliceous shear zone 1 to 2 m wide and striking 310 degrees, contains lenses and veins of hydrothermal quartz and 5 to 20-cm-thick zones of chrysocolla and malachite. The shear dips 80 to 85 degrees eastwards and is at or near a contact between silicified, epidotized pillowed metabasalt to the east and metarhyolitic agglomerate to the west. An open stope 9 m long, 1.5 m wide and collapsed at 7 m depth has been mined in the shear. The wall rocks are kaolinized and partly silicified. Although the shear extends for several hundred metres the mineralization appears to be localized. In 1955-1956, 151.88 t of cupreous ore averaging 17.34 per cent copper were produced. Chalcocite and chalcopyrite were encountered at about 9 to 10 m depth.

BOOBINA CREEK PROSPECT

Boobina Creek prospect (21°40′30″S, 119°56′50″E) is 3.2 km southwest of Copper Hills mine in metabasaltic country rocks dipping at 70 degrees to the east-southeast. Malachite, azurite, cuprite and limonite occur in a vertical quartz vein trending 310 degrees. The vein has been prospected by gougings to 9 m depth.

COPENHAGEN WEST PROSPECT

A small show of secondary copper minerals has been reported from this locality (21°18′40″S, 119°47′50″E), 16 km south-southeast of Marble Bar. The show is associated with chert marking a change from mafic to ultramafic rocks forming the core of the Warrawoona Syncline. In 1954, 2.09 t of cupreous ore was produced from an occurrence (21°16′50″S, 119°46′30″E) 3 km to the north-northwest, near Wyman Well.

SHARK GULLY OCCURRENCE

A limonitic, copper-stained quartz vein is present in a thin pelitic horizon in metabasalt at this occurrence (21°24′40″S, 119°36′40″E) 31 km south-southwest of Marble Bar. A sample of limonitic material assayed 0.69 per cent copper, 280 ppm lead, and 660 ppm zinc.

NORTH SHAW GOLD MINING CENTRE

Many of the gold mines at this centre (21°21′30″S, 119°22′40″E) contain copper minerals. Metabasalts at the northern margin of the Shaw Batholith contain fissure filling, quartz-gold-copper veins which commonly strike about 025 and 285 degrees, and are less than 1 m thick. The Roy Hill (Alpha) copper mine produced 7.89 t (1.93 t copper) in 1907. Small parcels of cupreous ore were produced from 3 PA's from 1955 to 1959 and totalled 5.06 t averaging 15.89 per cent copper.

WILSON MINE

Wilson mine (21°04′30″S, 119°12′10″E) is in east-northeast striking metabasalt near the southeastern margin of the Carlindi Batholith. A sporadically copper-stained quartz-limonite vein up to 30 or 40 cm thick occupies a shear striking 324 degrees and dipping 70 degrees to the east. A collapsed open cut 20 m long may have been opened to 15 m depth originally. On the same vein 15 m to the north is a small gouging 3 m long and 1 m deep. Recorded production is 13.81 t of cupreous ore averaging 15.02 per cent copper, which was raised in 1964-1965.

WOODSTOCK STATION AREA

Woodstock copper-gold deposit (21°38′40″S, 199°00′30″E) is 5 km east of Woodstock homestead in an inclusion of amphibolite enclosed by granitoid and gneissic rocks of the Yule Batholith. A quartz vein in the amphibolite has been pitted for about 40 m along its strike. Weak copper carbonate mineralization is exposed over a maximum width of 1 m. In 1958, 9.09 t of cupreous ore averaging 8.12 per cent copper was extracted (GML 1141).

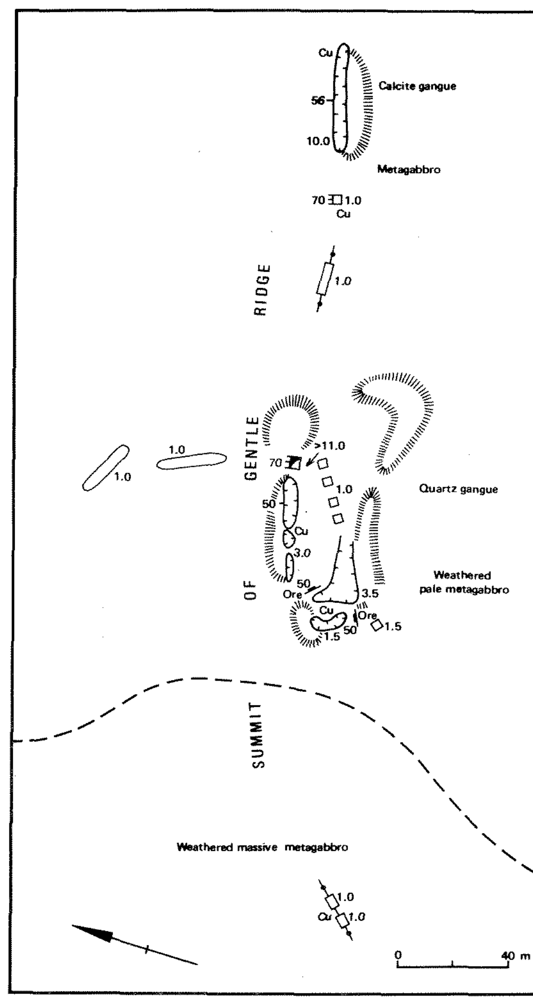


Figure 20. Surface plan of Lionel copper workings

At Mount Webber Southwest (21°39′20″S, 119°06′10″E) some 16 km east-southeast of the homestead, tantalite-bearing pegmatite veins in metabasalt contain minor amounts of copper minerals.

BLACK GIN POINT PROSPECT

This prospect (21°12′20″S, 118°22′00″) is 10 km north-northwest of Yandearra homestead in northeast-striking, fine to medium-grained amphibolite at the northwestern margin of the Yule Batholith. Thin laminated quartz veins dip steeply southeast, and appear to be emplaced about parallel to the strike of the amphibolite. The margins of these veins contain disseminations and smears of malachite, wolframite and scheelite. Shallow pits dug in the veins extend over 200 m of strike.

WEERIANNA GOLD MINING CENTRE

There are two copper producing areas at this centre. They are located 2.5 km west of Roebourne in rugged hills of metagabbro and foliated metabasalt, intruded by granitoid rocks occupying flat areas between the ridges. The main gold producing area at Weerianna lies 1.4 km to the north-northwest on the northern edge of the hill country.

The bulk of the production came from the Lilly Blanche mine (20°48′20″S, 117°06′40″E) in 1907, and amounted to 1 030.25 t of copper ore (193.01 t copper). A cupriferous quartz-limonite vein occupies a sub-vertical shear trending northeast. The surface indications of copper mineralization were weak and thin, but at 12 m depth (just above the water table) a shoot of ore 23 m long and up to 1.2 m wide was exposed. Chalcopyrite and pyrite passing upwards into massive pods of cuprite and malachite were encountered near the water table. The ore was open cut in the central portion and stopped upwards along its lateral extensions. Two shafts were sunk to the 12 m level.

The Ena workings are 300 m south and southeast of Lilly Blanche. There are many small north-northeast and northeast-striking, sub-vertical cupriferous limonite-quartz veins in the area. Several of these veins have been pitted or gouged for pods of oxidized copper ore. In 1907-1908, 26.92 t of copper ore (3.71 t copper) were produced and in 1963 2.80 t of cupreous ore averaging 10.30 per cent copper were extracted.

CARLOW CASTLE AREA DEPOSITS

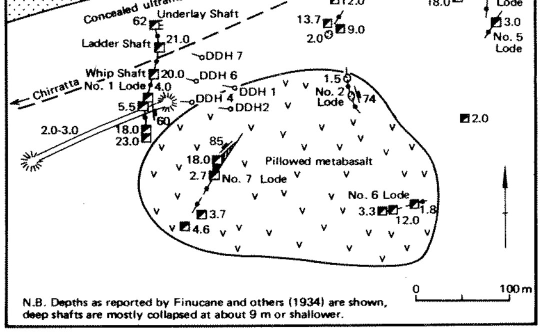
The Carlow Castle area is 9 km west-southwest of Roebourne, adjacent and south of the Roebourne-Chirratta road. A prominent ridge of folded but generally east-northeast striking and steeply south dipping pyritic banded chert bounds the area to the north. Scree from this ridge largely conceals a thin sill-like serpentinite unit immediately to the south. The three mineralized centres at Carlow Castle, Good Luck and Fortune are within various types of mafic igneous rocks which crop out as low hills for some 2.5 km south of the chert ridge.

The Carlow Castle (including the Quod Est, Wait-a-While and Federation leases) copper-gold workings (20°48′20″S, 117°03′40″E) are immediately south of the chert ridge in tholeiitic metabasalt. Seven, thin, steeply dipping quartz-limonite-copper-gold veins occupy generally north-trending shears in the metabasalt (Fig. 21); they have been numbered 1 to 7 (Montgomery, 1907). The bulk of production was from supergene ore at the 21 m level in the No. 1 Lode (averages 1 m thickness at this level) with subordinate amounts from No. 2 (Wait-aWhile) and No. 3 Lodes. Recorded production is 1 041.07 t of copper ore (163.53 t copper) which also included 19.87 kg gold and 7.85 kg silver, and 25.94 t of cupreous ore averaging 8.10 per cent copper. The oxidized-supergene mineralogy of the cupriferous veins and shears is limonite, cuprite, malachite and azurite with chalcocite, covellite, bornite and chalcopyrite appearing near the water table (about 20 m depth). Minor amounts of native copper and gold are present. The No. 1 and 3 Lodes contain cobalt and nickel minerals. These minerals (e.g. cobaltite) increase in amount northwards reflecting the ultramafic composition of some of the wall rocks here. Five inclined diamond drillholes totalling 551 m were put down by Consolidated Gold Mining Areas NL in 1968-1969 to test a broad induced polarization anomaly coincident with No. 1 Lode. In drillholes 1, 4 and 6 three quartz-chalcopyrite veins 0.23 to 0.76 m thick were encountered. The highest grade intersection was 0.7 m assaying 7.2 per cent copper, 1.42 per cent cobalt and 14.11 g/t gold in DDH4, but disseminated pyrite-chalcopyrite mineralization occurs between the veins and this assayed 0.86 per cent copper over 17.17 m in DDH4.

Amax carried out geological, geochemical and geophysical surveys followed by percussion and diamond drilling in the Carlow Castle area in 1969-1972. Surface and auger geochemical sampling in the Carlow Castle mine area outlined an anomaly immediately southwest of No. 1 Lode. A costean 145 m long (Fig. 21) put in to test this anomaly averaged 0.38 per cent copper, entirely within metabasalt containing some thin mineralized shears. Percussion drilling of the anomaly to 18 m vertical depth returned an average value of only 0.27 per cent copper.

The main exploration effort by Amax was to test the chert and serpentinite units for stratabound copper-zinc and nickel-copper mineralization respectively, and to test a layered mafic-ultramafic complex 1.5 km east-southeast of Carlow Castle mine for nickel-copper deposits. Drilling in the chert intersected layered or disseminated pyrite and pyrrhotite which, with the exception of 3.05 m assaying 4.4 per cent zinc at the base of a 6.10 m-thick sulphide zone adjacent to the serpentinite in diamond drillhole CCD6, were poor in base metal. Significant nickel-copper sulphides were not found in the serpentinite. In the layered complex pyrrhotite was found as a matrix mineral in serpentinized pyroxenite, the only nickel-copper sulphides encountered being in a 5 cm thick massive sulphide lens or vein.

The Good Luck (Brown and Norths) copper-gold mine (20°49′10″S, 117°04′20″E) is 1.5 km southeast of Carlow Castle mine. The principal working is in a short quartz vein, striking 080 degrees and dipping 85



GSWA 17280

Figure 21. Surface plan of Carlow Castle gold-copper workings

degrees to the south, emplaced in feldspathic metagabbro. The vein is 0.45 m thick at the surface, where copper carbonates and oxides accompany limonite, and 1.07 m thick at 21 m depth (water table) where chalcocite, pyrite and chalcopyrite were encountered. In 1917-1918, 5.29 t of copper ore (1.03 t copper) were produced. Several other small cupriferous quartz-limonite veins were prospected in the area.

The Fortune copper-gold workings (20°49′40″S, 117°04′20″E) are 2.2 km south-southeast of Carlow Castle mine in two *en echelon* quartz-filled shears striking east-northeast and dipping steeply northwestwards. The country rocks are metagabbro and metadolerite. Workings are most extensive on the quartz vein (mean thickness 1.5 m) emplaced in the eastern shear which has been opened up for 300 m and is marked by a 10-m-wide and 20-m-long barren quartz blow near the centre. The western quartz-filled shear has been traced for 150 m and averages 2.4 m in width. Shafts extended down to the water table (about 20 m deep). The mineralized assemblage is similar to that at Good Luck, and occurs in, and marginal to, the main veins. Copper ore was mined from 1901 to 1919 and totalled 419.01 t (80.36 t copper), and 14.08 t of cupreous ore averaging 13.00 per cent copper was produced in 1963-1964.

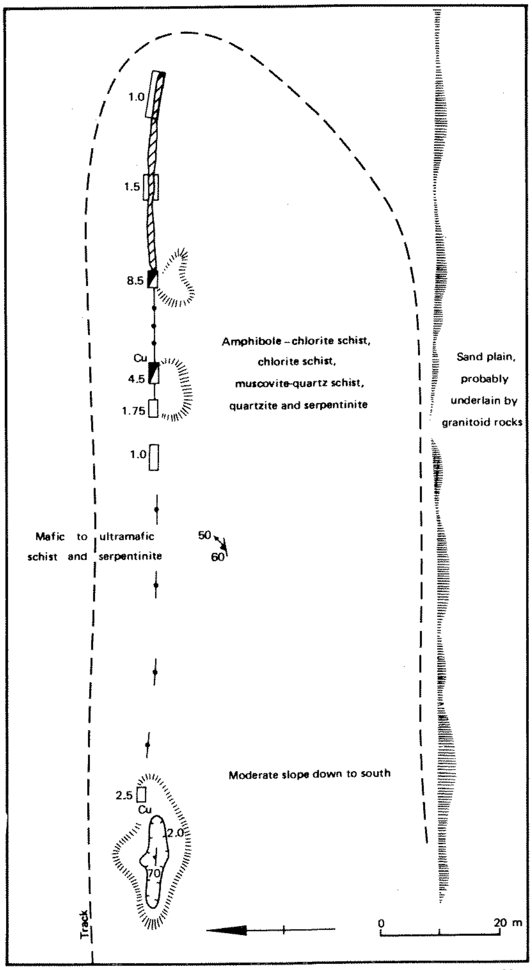


Figure 22. Surface plan of Tom Well copper prospect

CANHAMS PROSPECT

Canhams prospect (20°57′10″S, 116°51′50″E) is 25 km south of Karratha. It is located at a north-northwest striking contact between strongly recrystallized feldspathic metabasalt and porphyritic meta-rhyodacite, both of which are pyritic. Mafic metavolcanic rocks predominate in the area. A pit 1.5 m in diameter (representing a collapsed shallow shaft) is sited on a small pod of quartz-goethite-malachite-chrysocolla mineralization.

TWIN TABLE PROSPECT

This small prospect (20°54′20″S, 116°50′50″E) is 20 km south of Karratha in metabasalt. It consists of a 4 m deep shaft sunk on a thin shear striking 335 degrees and dipping vertically or 45 degrees to the east. Spoil indicates that cupriferous limonite-quartz veinlets and lenses up to 10 cm thick occupy the shear. Malachite staining is also present in the adjacent sheared metabasalt.

TOM WELL PROSPECT

Tom Well prospect (20°46′00″S, 116°50′00″E) is 5 km south-southwest of Karratha at the southern base of an east-west range of hills formed by mafic to ultramafic metavolcanic rocks. A quartz-goethite-malachite-chrysocolla vein strikes 090 degrees and is vertical or steeply north-dipping (Fig. 22). This vein occurs in a strongly foliated and lineated sequence of mafic to ultramafic schist containing muscovite-quartz schist and quartzite on the south side of the vein. The schist sequence is probably in contact with granitoid or gneissic rocks 50 m south of the vein. Shallow openings in the vein extend over 140 m. A few tonnes of ore appear to have been extracted from the western end of the workings but no production has been recorded.

MAITLAND COPPER MINE

This small mine (21°04′40″S, 116°52′30″E) occurs in mafic metavolcanic rocks 4 km west of Whundo mine. A production of 37.99 t of cupreous ore averaging 8.08 per cent copper has been recorded.

SHEPHERDS WELL PROSPECT

This prospect (21°02′00″S, 116°19′10″E) has not been visited, but is probably a copper show related to shear or quartz vein in metabasalts in the core of a narrow north-east striking supracrustal belt in the extreme west of the Pilbara Block.

GRANITOID HOST ROCKS

COOKES CREEK GRANITE OCCURRENCES

Minor occurrences of malachite have been reported from this cross-cutting granitoid pluton located on the eastern flank of the McPhee Dome, 45 km north-east of Nullagine. The occurrences are associated with wolframite and scheelite-bearing quartz veins.

BOODARRIE STATION DEPOSIT

This small deposit (20°39′20″S, 118°41′20″E) is 7.8 km south of Trig Hill and is immediately east of the Port Hedland-Wodgina road. Disseminated malachite occurs in a small quartz vein 46 m long and trending 346 degrees, emplaced in granitoid gneiss. Mineralization is weak and is present over a maximum width of 5 m. Shallow pits lie on the vein, and 1.22 t of cupreous ore averaging 5.90 per cent copper was produced in 1956.

MOUNT FRANCISCO DEPOSIT

This deposit (ca. 21°23′00″S, 118°33′20″E) is about 1 km south of Mount Francisco and probably consists of a small quartz vein with malachite disseminations in granitoid country rocks. The occurrence has not been accurately located. In 1957, 4.23 t of cupreous ore containing 4.23 per cent copper was produced (PA 2529).

BASSETS PROSPECT

Bassets prospect (21°06′40″S, 118°31′00″E) is 1.3 km at 165 degrees from Kangan homestead. Three shallow pits were dug in a 250 m long and 2 m wide quartz vein in weathered granitoid. Disseminated malachite occurs over the total length of the vein but the main cupriferous zone is 80 m long and 2 m wide.

COPPER-NICKEL DEPOSITS (TYPES E AND F)

COPPER DOMINATED MINERALIZATION

The Mount Sholl copper-nickel prospects (20°55′30″S, 116°55′40″E), some 23 km south of Karratha, are the only important examples. The prospects are at two localities on the northern margin of an irregular, metamorphosed gabbroid intrusion 6 km by 5 km in outcrop area. The intrusion has been emplaced into northeast-striking mafic to felsic metavolcanic rocks and is partly disrupted by later faulting. The bulk of the intrusion consists of monotonous, unlayered metagabbro which may form bold hilly terrain. A thin margin of low lying, poorly exposed, serpentinized feldspathic peridotite is present in the northwest, (B2 prospect) and a thin, sill-like tongue of gabbro and peridotite extends 3 km from the northeastern margin of the intrusion (A1 prospect).

Mineralization is visible at the surface at the A1 prospect and takes the form of copper-stained limonitic metaperidotite exposed in shallow gouges. These shows occur in the western half of the low ridge marking the outcrop of the intrusive tongue. Diamond drilling by Whim Creek has shown that the tongue dips to the north-northwest at 40 to 50 degrees and consists of a core metaperidotite enclosed by metagabbro. This mineralogical zoning has also been established by drilling at the B1 prospect which consists of a wedge-shaped (in cross-section) margin to the main intrusion, that dips at about 25 degrees to the east-southeast. Surface shows of mineralization are absent at the B1 prospect which however contains the bulk of the mineralization discovered in the intrusion. It is not clear whether this wedge-shaped feature is wholly primary or partly the result of deformation. Nickel-copper ratios are variable. Some of the better intersections are 16.8 m assaying 1.31 per cent nickel and 1.38 per cent copper and 4.6 m assaying 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 (Ni:Cu = 0.83), using a 0.5 per cent nickel plus copper cut off figure.

NICKEL DOMINATED MINERALIZATION

The Sherlock Bay nickel-copper prospect (20°48′50″S, 117°32′26″E) is 40 km east of Roebourne in a featureless plain. The area of the prospect is marked by small, low ridges striking east-northeast. An occurrence of malachite-stained limonite in a weathered quartz-amphibole schist and metagabbro on the margin of one of these ridges is shown on the Roebourne Geological Sheet (Ryan, 1966). Since 1967 Australian Inland Exploration (Texasgulf) have investigated the occurrence (Miller and Smith, 1975). Drilling has delineated four east-northeast striking mineralized zones (pyrite-pyrrhotite-pentlandite-chalcopyrite) in a subvertical layered quartz-actinolite-stilpnomelane-calcite-magnetite-sulphide schist unit traced for 4.5 km. This unit occurs in a complex sequence of felsic and chloritic schist, recrystallized chert, metagabbro, amphibolite and serpentinized peridotite forming a lensoid belt up to 1 km wide, enclosed by gneissic and deformed granitoid rocks. The eastern two ore zones (500 m and 1 000 m long, up to 40 m wide) are nickel rich (Ni:Cu $\approx$ 5) but the western two zones (Nos. 3 and 4 zones) are copper rich (Ni:Cu $\approx$ 0.25). The No. 3 zone is 1 000 m long and 10 to 40 m wide, and averages 0.3 per cent copper and up to 0.05 per cent nickel. Several pipe-like shoots make up the No. 4 zone: the largest pipe is 200 m long and 30 m wide, and averages 0.24 per cent copper and 0.1 per cent nickel over 30 m. The best copper values in the eastern ore zones are about 0.5 per cent. Miller and Smith (1975, p. 172) estimated resources of 75 Mt of 0.5 per cent nickel and 0.1 per cent copper for these two ore zones.

The Ruth Well nickel copper prospect is 16 km south of Karratha. It occurs in an easterly striking supracrustal belt in a sequence of komatiitic and tholeiitic metabasalts containing lenses of metaperidotite. A small lens of iron-nickel-copper sulphides is associated with massive magnetite aggregates (up to 7 m thick). The best intersections were of about 3 m of 8 per cent nickel, the maximum copper values were 10 per cent.

OTHER OCCURRENCES

COOBINA CHROMITE DEPOSIT

Minor amounts of secondary copper minerals are known from this deposit (23°29′30″S, 120°17′00″E) which is contained in a serpentinite intruded into granitoid and metamorphic rocks of the eastern Sylvania Dome (Bye, 1975).

PRAIRIE DOWNS PROSPECTS

These prospects (23°43′00″S, 119°17′00″E) occur at the southwestern margin of the Sylvania Dome in a partly quartz-filled fault zone which trends west-northwest. This fault is known as the Prairie Downs Fault, and in the area of the prospect it transects steeply dipping Archaean metabasalt and metadolerite. The fault does not impinge upon gently dipping Proterozoic quartz conglomerate and grit which unconformably overlie Archaean rocks west of the fault.

Lead-zinc and minor copper mineralization has been found sporadically in association with the vein quartz, accompanied in places by pods of barite, calcite and gypsum. Surface exploration and drilling by Australian Ores and Minerals—Hill Minerals N.L. in 1970-1972 encountered mineralized true thicknesses averaging 2 to 3 m. These intersections consisted of sphalerite and galena with minor pyrite and chalcopyrite in (i) veins and stringers in quartz, (ii) in sheared metabasic rock, and (iii) massive pods up to 0.5 m thick. The mineralization is very irregular in geometry, concentration and grade, and with the exception of two thin (< 1.5 m thick) intersections copper values in diamond drill core were less than 0.5 per cent. Remaining surface showings of copper mineralization are rare and weak. The prospects have little promise as a copper property.

CHAPTER 9

Paterson Province

GEOLOGY

The regional geology of the province has been summarized briefly by Williams and others (1976). It strikes north-northwest and is 600 km by 125 km in area as presently exposed. The two major lithostructural components of the province are: (i) the Rudall Metamorphic Complex composed of interfolded gneissic and metasedimentary rocks and syntectonic (with respect to gneiss formation) granitoids, and (ii) the younger, unconformably overlying Yeneena Group which is a cratonic cover sequence of variably deformed and metamorphosed clastic rocks (Table 22). The folding and cleavage development affecting the Yeneena Group was unaccompanied by significant regional metamorphism. However contact metamorphism up to the hornblende hornfels facies has locally recrystallized rocks of the group near granitoid intrusions or in domal structures (e.g. Telfer) which may be cored by such intrusions.

The Rudall Metamorphic Complex (Chin, in prep.) crops out in the central-eastern part of the province, and constitutes about 20 per cent of the exposed area of the province. About two-thirds of the complex consists of various gneisses, dominantly granitoid but also including amphibolitic and metasedimentary types, quartzite and quartz-magnetite rocks. The lithological association is suggestive of a reworked Archaean rock assemblage, although the typical metallogenesis of Archaean terrains in the State seems to be lacking. The presence of relict sillimanite, diopside and staurolite indicates that the gneiss-forming event was associated with high-grade regional metamorphism. The other major component of the complex is a cover sequence, younger than the gneiss, which consists of quartzite and quartz-mica schist with subordinate graphitic schist, biotite-garnet schist, banded marble and metamorphosed banded iron formation. This sequence has undergone upper greenschist facies metamorphism but not the earlier higher grade metamorphism affecting the gneiss (Table 22). Retrogressive mineral reactions in the gneiss are ascribed to the later greenschist facies metamorphism (Williams and others, 1976, p. 80).

TABLE 22. STRATIGRAPHY AND CUPRIFEROUS MINERALIZATION OF THE PATERSON PROVINCE

Major unit	Formation or lithology		Mineralization and remarks
	Bangemall Group or Phanerozoic cover rocks		
	Unconformity		
Yeneena Group[1]	*Paterson Range area*	*Remainder*	
	Wilki Quartzite		
	Punta Punta Formation		Clastic carbonates;
	Telfer Formation		Gold-copper in quartz saddle reefs;
	Malu Quartzite		Pyritic; Cupriferous quartz veins
	Isdell Formation	Isdell Formation	Minor Cu in dolomite;
		Choorun Formation	Siltstone—sandstone;
		Broadhurst Formation	Minor Cu in siltstone and shale
		Coolbro Sandstone	
		Googhenama Conglomerate	
	Unconformity (folded)		
Rudall Metamorphic Complex			
	5. Pegmatite dykes		
	Deformation and greenschist facies metamorphism		
	4. Small meta-peridotite and meta-pyroxenite intrusions		
	3. Metasedimentary cover sequence of schist and quartzite		Minor Cu in carbonate iron-formation
	Highly deformed unconformity		
	2. Strongly foliated, porphyritic adamellite		
	1. Gneiss and amphibolite, may include reworked Archaean rocks		Minor Cu in quartz veins and quartz-magnetite rock

[1] Intruded by Mount Crofton Granite which has an Rb-Sr age of 614 ± 42 m.y. (Trendall, 1974)

MINERALIZATION

Known cupriferous mineralization appears essentially stratabound and is known from several parts of the stratigraphy (Table 22). However, the only important occurrences found to date are the auriferous quartz-pyrite-chalcopyrite saddle reefs occurring in the Telfer Formation (Yeneena Group), exposed in elongate domal structures developed in the northern part of the province.

RUDALL METAMORPHIC COMPLEX (TYPES A AND C)

Five occurrences are known. Two occurrences (Camel Rocks and Yandagooge) are in the metasedimentary cover sequence within metamorphosed carbonate iron formation, associated with quartz, mica and garnet bearing schists. Three other occurrences are within basement rocks to this cover sequence. Copper mineralization appears weak which, together with the remoteness of the area, make the occurrences of little or no economic interest.

The Camel Rocks copper prospect (22°34′20″S, 122°38′00″E) is on the northeastern edge of the complex in an isolated outcrop of steeply southwest-dipping rocks, 14 km at 005 degrees from Mount Eva. A layered magnetite-chlorite-garnet-sericite quartzite, up to 35 m thick, contains concordant zones of limonite and manganese staining and pyrite pseudomorphs over a strike length of about 400 m. Small isolated patches of disseminated malachite occur where the quartzite is involved in two folds plunging steeply to the southeast. Exploration by Newmont in 1974-1975 included the boring of two diamond drillholes, which showed that the quartzite is ankeritic at shallow depth but contains only minor pyrite and chalcopyrite. The best mineralization encountered was a 2 m intersection (at about 90 m vertical depth) assaying 0.43 per cent copper corresponding to coarsely recrystallized ankerite containing magnetite-chalcopyrite-pyrite veinlets. A slightly deeper 2 m intersection in the same drillhole assayed 0.25 per cent copper.

The Yandagooge prospect (22°19′20″S, 122°04′10″E) is in the northwestern extremity of the complex in steeply north-dipping rocks forming a short strike ridge on the west side of Yandagooge Creek. The prospect was discovered by Otter in 1971. A thin gossanous horizon, anomalous in copper, lead and zinc, extends discontinuously over about 1.2 km of strike. Quartz-andalusite-graphite-garnet (-?pyrite) schist structurally overlies the gossan and quartz-mica schist underlies it. The gossan is developed in a layered quartz-ankerite/siderite rock. Some 3 km to the southwest small quartz-carbonate veins contain galena and sphalerite.

The South Rudall Dome prospects (22°50′10″S, 122°34′40″E) are near the southern edge of the complex and were investigated in 1974-1975 by Newmont. The prospects occur on the western flank of a small domal structure elongated north-south. This dome is cored by garnetiferous amphibolite succeeded outwards by a thin (10-40 m) layered quartz-magnetite rock overlain in turn by quartz-sericite schist. These rocks probably belong to the basement sequence. Very narrow and discontinuous gossanous horizons, anomalous in copper and zinc, occur concordantly in the quartz-magnetite rock over about 2 km of strike. The mineralized horizons themselves consist of graphite, sericite, chlorite, quartz, magnetite and carbonate with boxworks after pyrite, pyrrhotite, chalcopyrite and a trace of sphalerite and galena.

The Mount Cotten prospect (22°49′10″S, 122°35′40″E) is 5.8 km north-northeast of the South Rudall Dome prospect on the southwestern side of an isolated hill (Mount Cotten). The hill is formed by a graphitic banded quartzite defining the nose of a fold plunging at about 35 degrees towards 355 degrees (mineral lineation). A limonitic quartz vein occurs on the western limb of the fold and strikes north-northeast. It is emplaced in knotted quartz-muscovite schist.

The Mount Cotten Northeast prospect is 4.2 km northeast of Mount Cotten. Quartz-muscovite-biotite schist strikes northeast to east-northeast and contains a sub-concordant quartz vein. Malachite and copper oxides occur over a 150 m strike length of the vein. A surface sample assayed 9.3 per cent copper, 370 ppm lead and 33 g/t silver. The prospect appears to be on the west limb of an antiformal fold plunging at 50 degrees towards 070 degrees.

An unnamed occurrence at 23°00′10″S, 122°58′20″E (Gunanya Sheet) consists of a thin cupriferous quartz blow emplaced in amphibolite within a granitoid gneiss. Malachite, limonite and pyrite occur in patches in the quartz. A surface sample assayed 5.68 per cent copper, 5 300 ppm lead, 2 200 ppm zinc, 730 ppm nickel and 17 g/t silver.

YENEENA GROUP ROCKS (TYPE C)

BROADHURST FORMATION

Minor occurrences of copper-stained or copper-anomalous limonitic quartz veins have been noted from this formation on the Paterson Range (Chin and Hickman, 1977) and Rudall (Chin, in prep.) Sheets.

ISDELL FORMATION

Malachite-chrysocolla-chalcocite mineralization occurs as small pods within irregular, discordant bodies of recrystallized brecciated dolomite in thinly bedded dolomites and siltstone in the Karakutikati Range (formerly known as the Parallel Range), 10 to 15 km south-southwest of Telfer. The main prospect (21°49′20″S, 122°08′50″E) is 14 km south-southwest of Telfer in the hinge zone of a major anticlinal fold. Secondary copper minerals, limonite and manganese oxides present in pods up to a few metres in size occur in a mass of recrystallized dolomite about 20 m square in outcrop area. Shallow drilling by Newmont here, and at similar prospects 1.5 km to the east and 2.1 to 2.4 km to the southeast, has encountered narrow intersections (1 to 3 m) of secondary copper mineralization assaying up to 4.2 per cent copper. Anomalous gold values were found at some prospects.

MALU QUARTZITE

Much of this formation contains accessory pyrite and stratabound quartz veins are locally gossanous on the Paterson Range Sheet (Chin and Hickman, 1977). A group of such occurrences in an anticlinal structure 10 km north of Telfer assayed up to 0.27 per cent copper from surface samples.

TELFER FORMATION

This formation is a succession of alternating metamorphosed quartzite (some pyritic) and calcareous shale members totalling 500 to 800 m in thickness. The pelitic members in the Telfer Dome consist of quartz and muscovite with subordinate to accessory garnet, ilmenite, zircon, rutile, tourmaline and pyrite.

At the Telfer mine (21°43′30″S, 122°12′30″E), saddle reefs of auriferous quartz and quartz-limonite form stratabound ore bodies in the metamorphosed calcareous shale members at several stratigraphic levels in the formation (Blockley, 1974). Published reserves are 3.8 Mt of ore averaging 9.6 g/t of gold. The main reef is up to 2.5 m thick, and is traceable for 4 km around the dome. In the upper part of the oxidized zone (surface to 40 to 50 m depth), copper is more or less completely leached from the reefs, which consist of quartz and limonite at the surface and contain supergene concentrations of gold in limonite. Chrysocolla and chalcocite are present from 60 to 100 m depth. Supergene enriched assemblages of chalcocite, minor bornite and sparse native copper accompanying pyrite and chalcopyrite, occur from about 100 to 150 m depth. Primary sulphide mineralization is present below 150 m. Here the gold occurs as inclusions in pyrite, accompanied by chalcopyrite. Minor occurrences of this type of mineralization are known in the Telfer Formation 25 km east and 13.5 km northwest of Telfer, and in unassigned Yeneena Group rocks 31 km and 34 km east-northeast of Telfer (Chin and Hickman, 1977).

CHAPTER 10

Hamersley Basin

GEOLOGY

The Lower Proterozoic sedimentary and volcanic rocks of the Hamersley Basin as defined for the study, have an outcrop area of some 95 000 km² (Plate 1). The stratigraphy of the Mount Bruce Supergroup, which encompasses the rocks of the Basin, is summarized in Table 23. From the base upwards the three component groups of the supergroup are essentially (a) a basal clastic and mafic volcanic sequence (Fortescue Group), (b) a chemical sedimentary sequence (Hamersley Group) and (c) an upper clastic sequence (Wyloo Group). Attention has been drawn by several authors to the similarities in basin development and mineralization between the Hamersley Basin and the Transvaal Basin in South Africa (e.g. Trendall, 1968; Button, 1976).

Along the northern edge of the basin, the Fortescue Group dips gently southwards off the Pilbara Block. South of this unconformity, the intensity of folding gradually increases, and the metamorphic grade attained rises from prehnite-pumpellyite to the greenschist facies (R. E. Smith, 1975a). Steep dips, local overturning and the development of a slaty cleavage characterize the southern margin of the basin. In terms of the definitions used for this bulletin the southwestern margin of the basin is regarded as transitional to the Gascoyne Province. Metamorphic grade and the intensity of axial surface fabrics increase southwestwards. Where not concealed by cover rocks of the Bangemall Basin the western limit of this transitional zone is taken to be defined by the appearance of granitoid plutons (radiometric age probably around 1 700 m.y.) intrusive into metamorphosed rocks of the Wyloo Group.

MINERALIZATION

Cupriferous mineralization (Table 23) is sparse, and most occurrences are in the transitional zone or the folded southern portion of the basin in the Jeerinah, Ashburton and Capricorn Formations. Past production amounts to 270 t of copper ore and 487 t of cupreous ore (Table 24), though official records are incomplete. Quartz veins or shears and fractures carrying disseminated iron and minor copper sulphides (with or without gold) and supergene enrichments of stratiform iron-copper sulphides represent the commonest types of occurrence. In the case of the basalts of the Fortescue Group and the Jeerinah Formation shales, occurrences in veins and fractures may correspond to syngenetic copper mobilized hydrothermally and/or by meteoric ground water into structural sites. Mineralization in the Ashburton and Capricorn Formations may be more varied mineralogically, but is localized and volumetrically very small. Copper minerals accompany silver-lead-zinc mineralization and vice versa, with the addition of minor amounts of antimony, bismuth and uranium bearing minerals in the Ashburton Downs area. In some cases syngenetic polymetallic mineralization in the Capricorn Formation may have been leached out and redeposited into structural sites in the underlying Ashburton Formation.

TABLE 23. STRATIGRAPHY AND CUPRIFEROUS MINERALIZATION OF THE HAMERSLEY BASIN

Group	Formation	Mineralization and remarks
Wyloo Group	Capricorn Formation Ashburton Formation	Cupriferous quartz veins and shears, some polymetallic
	Duck Creek Dolomite	Rare cupriferous quartz veins
	Mount McGrath Formation Beasley River Quartzite Turee Creek Formation	
Hamersley Group	Bolgeeda Iron Formation	
	Woongarra Volcanics	Sparse disseminated Fe-Cu sulphides
	Weeli Wolli Formation	Sparse disseminated Fe-Cu sulphides
	Brockman Iron Formation Mount McRae Shale Mount Sylvia Formation	
	Wittenoom Dolomite[1]	Rare small supergene copper deposits
	Marra Mamba Iron Formation[2]	
Fortescue Group	Jeerinah Formation[2]	Weakly cupriferous pyritic carbonaceous shales and slates
	Maddina Basalt[3,5] Kuruna Siltstone[3,4] Nymerina Basalt[3,4,5] Tumbiana Formation[3,4] Kylena Basalt[3] Hardey Sandstone[6] Mount Roe Basalt	Cupriferous quartz veins and shears in volcanics
	unconformity	
	Archaean rocks of the Pilbara Block	

1. Equivalent to the Carawine Dolomite in the northeast
2. Partly equivalent to the Lewin Shale in the northeast
3. Equivalent to the Mount Jope Volcanics on Mount Bruce and Roy Hill Sheets
4. Equivalent to the Pillingini Tuff on Pyramid and Yarraloola Sheets
5. Equivalent to Pearana Basalt in Gregory Range area (Yarrie Sheet)
6. Equivalent to Cliff-Springs Formation on Pyramid and Yarraloola Sheets

R. E. Smith (1975a, 1975b, 1976) has defined regionally extensive hydrothermal alteration affecting the flow tops of units in the Maddina Basalt (Fortescue Group). The Chichester Ranges area, on the northern side of the Basin, was regarded as the major area of interest. He suggested that the alteration was related to hydrous burial metamorphic processes, and, as such, parallels the setting of the copper mineralization in the Portage Lake Lava Series of the Proterozoic Keweenawan sequence in Michigan, U.S.A. The cupriferous pyritic shale deposits in the Nonesuch Shale at White Pine, Michigan may owe their copper contents to the replacement of pyrite with chalcocite, by copper-bearing fluids migrating upwards from source areas in altered and leached Keweenawan basalts. Smith (1976, p. 6) goes on to propose that, by analogy, copper precipitation could occur up dip of altered Maddina Basalt where ore fluids come into contact with pyritic sediments such as the Roy Hill Shale member of the Jeerinah Formation. However copper occurrences are rare in the Fortescue Group basalts, especially in the northern part of the basin, and the cupriferous mineralization in the Jeerinah Formation shales is not of the White Pine type, and again is virtually absent in the north.

In summary the known cupriferous mineralization in the basin has proved to be of little economic importance. The prospects of making important discoveries do not seem very bright.

FORTESCUE GROUP (TYPES B AND C)

JEERINAH FORMATION

Introduction

The Roy Hill Shale Member is at the top of the Jeerinah Formation, and forms a poorly exposed tract below the scarp formed by the overlying Marra Mamba Iron Formation. The shales or phyllites are pale weathering, and may be variably silicified at the surface, but some are dark grey, carbonaceous and sulphidic at depth. Thin carbonate and cherty horizons are present in the shales. The amount of sulphide present varies from zero to 20 per cent exceptionally, and may average 1 to 5 per cent. The sulphides occur in thin laminae or lenses, small nodules or as disseminations. The bulk of this sulphide is pyrite with subordinate pyrrhotite and minor or trace amounts of chalcopyrite and sphalerite. Weathering of the pyritic carbonaceous shales, which may be regionally anomalous in copper and zinc, has enhanced primary copper contents from an average of perhaps 100 to 400 ppm (exceptionally up to 2 000 ppm), to 0.5 to 1.0 per cent copper in restricted zones (widths of a few metres), with exceptional values up to 3 per cent over very narrow intervals. The occurrences found to date are not considered to be of economic interest.

TABLE 24. MINE PRODUCTION OF COPPER FROM THE HAMERSLEY BASIN

Mine or Group	Copper ore and *concentrates* (t)	Cupreous ore and *concentrates* (t)	Average grade (%)	Contained copper (t)
Ashburton Downs (west of)		128.79	8.84	11.39
Balfour Downs (north of)		178.56	20.43	36.48
Belvedere	1.32		14.39	0.19
Cane Hill	223.00		34.39	76.68
Goobaroo Pool		3.31	15.91	0.53
Mount Blair South	3.71		42.05	1.56
		6.00	18.99	1.14
PA 339		1.79	23.82	0.43
Paulsen	8.45		16.57	1.40
Red Hill		47.07	15.03	7.08
Windy Ridge	20.37		12.67	2.58
		115.36	17.73	20.45
Wonmunna	13.53		25.60	3.46
		5.96	23.75	1.42
Totals	270.38	486.84	[1]21.76	164.79

1. Overall weighted average for copper and cupreous ore and concentrates combined.

This information derives largely from a regional exploration programme conducted by WMC in 1967-1972, which was based on soil geochemical sampling of more than 1 600 km strike length of the Jeerinah Formation. This coverage accounts for the bulk of the total extent of the formation in the Hamersley Basin. Only the upper part of the formation was found to be anomalous in copper. New occurrences of stratiform mineralization were found, carrying enhanced copper values in the oxidized zone, at (i) Brockman and Edneys prospects on the northern limb of the Jeerinah Anticline, 10 to 15 km north of Mount Brockman, (ii) south of Tom Price, and (iii) at several places in the Wonmunna area northwest of the Ophthalmia Range. Shallow drilling (total 11 634 m) was concentrated in these three areas, but latterly the main effort was directed towards new and old prospects at Wonmunna. Previously in 1953 an attempt was made to work the deposits at Wonmunna, but with little success. In 1964 the United States Metals Refining Company (Amax) examined the area and concluded that the occurrences were of no economic interest, regarding them as the result of supergene enrichment of syngenetic mineralization.

Wonmunna Area

In this area, some 60 km west-northwest of Newman, the Jeerinah Formation is intruded by dolerite sills and involved in east striking, gently doubly plunging folds, which are accompanied by a steeply north or south-dipping axial-planar, slaty cleavage. The Bull and Mount Robinson prospects were considered to be the most promising by WMC.

The Bull prospect (23°06′50″S, 119°06′00″E) is 21.6 km at 119 degrees from Mount Robinson and 3.8 km west of the old workings at Wonmunna itself. The prospect is just south of a dolerite sill, and mineralization is exposed in a small creek. Zones of cuprite, malachite and chrysocolla veinlets from a few to 30 cm thick are visible within a 25 m strike width. The host rocks are pale-grey slates, with carbonate-rich beds, dipping 65 to 75 degrees southwards, possibly being within a tight synclinal structure. The slaty cleavage is subparallel to the bedding and some mineralization is located within the cleavage rather than the bedding. There seems to be little continuity of mineralization along strike (scattered shows over 700 m strike length), and visible mineralization is unimpressive. The prospect was costeaned by Amax in 1964, and WMC put down two vertical diamond drillholes (total 132 m) and made two traverses of shallow vertical rotary holes. The best results of this drilling were 0.76 m of 1.79 per cent copper from oxidized slate in diamond drill core, and 10.67 m drilled width of 3.43 per cent copper from one rotary drillhole. Inclined drilling is needed for a proper assessment but there is little chance of this prospect gaining any economic importance.

The Mount Robinson prospect is 15.7 km west of Wonmunna, just north of a dolerite sill. Five north-south costeans along 140 m of strike expose a 25 m wide zone of grey to purplish grey calcareous shale containing nodules (up to 5 cm), laminae and subordinate veinlets of limonite (few millimetres thick) with stainings of malachite, cuprite and chrysocolla over more restricted widths of a few metres. There is no pervasive disseminated mineralization. Bedding dips 60 to 65 degrees northwards and a weak slaty cleavage dips steeply north or south and is axial planar to open flexural and drag folds plunging gently to the west. Three rotary drillhole traverses drilled by WMC indicated a mineralized zone (oxidized) at least 270 m long, 4.5 m wide and 18 m deep, assaying 0.2 to 2.3 per cent copper.

The Bend prospect is 8 km west of Mount Robinson prospect and consists of similar but weaker mineralization. Ironstone (or 252) prospect (23°07′50″S, 119°04′00″E) is shown on the Newman Sheet (Daniels and MacLeod, 1965) and is just south of a small laterite plateau. Six costeans expose about 250 m of strike below the laterite. White-weathering shales strike 290 degrees and dip moderately to steeply northwards and are deformed by shallowly west-plunging folds with axial-planar cleavage which may obscure the bedding. Two zones, of ochrous limonitic shale 25 m apart and less than 2 m thick, contain malachite-chrysocolla veinlets and stainings. There is little visible evidence of this mineralization except in one of the central costeans. The Central (Sleepy Hollow) prospect (23°07′50″S, 119°07′10″E) consists of five costeans (Amax) over about 250 m strike length, and a small shallow open cut in shales containing fine, pisolitic carbonate horizons. Strike is about 070 degrees but dips are variable because of widespread, open, asymmetric and symmetric minor folding. Thin stratabound zones up to 40 cm thick contain laminae and veins of limonite plus rare malachite and chrysocolla. The style of mineralization is similar to that of Bull prospect. The Central prospect is shown on the Newman Sheet.

Wonmunna (Wanna-Munna) prospect (23°06′30″S, 119°08′20″E) is 24.8 km at 111 degrees from Mount Robinson. Twelve costeans over a 300 m strike length were cut by Amax in interbedded dark grey shales, dark grey pisolitic carbonate and siliceous shale dipping steeply south. A steeply south-dipping slaty cleavage is axial planar to asymmetric minor folds. Mineralization is similar in style to the other prospects but is weak, thin, and has little strike persistence. Horizons of limonite nodules are common, but visible copper mineralization is now very sparse. Fine-grained disseminations of malachite were seen in carbonate-rich shale. Three lines of rotary drillholes put in by WMC into oxidized shale encountered little mineralization the best intersection being 3 m assaying 2.90 per cent copper. Silver-rich veinlets were found in some drillholes and zinc values up to 0.4 per cent occurred rarely. In 1953 a production of 13.53 t of copper ore assaying 25.60 per cent copper (3.46 t copper) and 5.96 t of cupreous ore averaging 23.75 per cent copper was recorded.

Other similar occurrences have been found in the area, but like the ones described they consist of minor supergene enrichment of iron plus very minor copper sulphide mineralization in seams, nodules and disseminations in carbonaceous slate or shale. The presence of dolerite sills in the sequence is incidental and apparently unrelated to the copper mineralization.

Other Prospects

Minthicoondunna (Mindi) prospect (22°44′40″S, 118°15′40″E) is on the northeastern flank of the Milli Milli Anticline, 360 m northwest of the outcrop of the base of the Marra Mamba Iron Formation. Small pits, 1 to 2 m deep, have been dug in white-weathering silicified shale with nodular, limonitic horizons. Only two pits contain copper-stained material in very small amount. A vertical diamond drillhole 110 m deep sunk by WMC encountered pyrite and pyrrhotite-bearing graphitic shale and siltstone assaying a maximum of 2 080 ppm copper. Most assays were considerably less than 1 000 ppm. This prospect is of no economic importance.

The Brockman and Edneys prospects (22°21′00″S, 117°18′00″E) are adjacent to each other in shales with interbedded cherts on the north-dipping limb of the Jeerinah Anticline. In 1967 a programme of five vertical drillholes (512 m total length) bored by WMC encountered a maximum of 1.62 m of 0.4 per cent copper. Low-grade oxidized copper mineralization over an average width of 8 m (3 Mt averaging 0.24 per cent copper) was indicated by sixty-seven percussion drillholes (average depth 30 m) put down at Brockman prospect by WMC in 1968. The best 1.6 m thick intersections assayed up to 0.7 per cent copper. Further shallow drilling in 1971 yielded a peak value of 4.6 m of 0.61 per cent copper.

Essentially barren iron sulphides in carbonaceous black shales of the Roy Hill Shale Member, which produce surface copper anomalies, have also been investigated at (i) Gregory Gorge in the northwestern Hamersley Range by Westfield in 1971-1973, and (ii) in the Three Corner Bore area at the eastern end of the Wyloo Anticline by Asarco in 1971.

REMAINING SEDIMENTARY FORMATIONS

As part of the regional prospecting programmme over the Jeerinah Formation, WMC also carried out some geochemical sampling over the Hardey Sandstone, which is near the base of the Fortescue Group. Two geochemical anomalies were found in carbonate-bearing, weakly pyritic, feldspathic sandstone and graphitic shale at the Beasley River prospect (22°47′10″S, 117°13′10″E). This locality is 14 km at 047 degrees from Cajaput Pool, on the western flank of the Rocklea Dome. Surface shows of copper mineralization occur in a 60 by 30 m area (elongate north-south) in a moderately west-dipping sequence. Two diamond drillholes (total length 228 m) intersected 1.6 m assaying 0.13 per cent copper and 2.4 m assaying 0.19 per cent copper.

The Baramine South prospect (20°53′00″S, 120°58′00″E) is 3km south of the abandoned Baramine homestead in the extreme northeastern part of the Hamersley Basin. This area contains the Braeside lead field (Blockley, 1971b). A silicified fault zone, striking north-northwest, contains secondary copper minerals (malachite, cuprite) locally, which have been prospected by a shallow shaft. Blatchford (1925, p. 81) reported taking a (channel) sample across a width of 1.4 m which assayed 25.32 per cent copper, 279 g/t silver and a trace of lead. This fault juxtaposes Lewin Shale to the east and Carawine Dolomite to the west.

VOLCANIC FORMATIONS

Braeside Lead Field

The Braeside lead field occurs on the northeastern edge of the Hamersley Basin in the Gregory Range area. Blockley (1971b, p. 124-141) has described the silver-lead mineralization of the field, which contains minor amounts of zinc and copper minerals and a trace of vanadium-bearing minerals. The bulk of the mineralization occurs in silicified fault zones striking north-northwest and cutting the Kylena Basalt. Copper minerals have been reported from the Ragged Hills mine (southern shoot), the Lightning Ridge workings (western shoot) and the North Koongalin prospect.

Two occurrences at the northern end of the field are copper prospects. The Baramine prospect (20°52′30″S, 120°57′30″E) is 2.5 km southwest of Baramine homestead (abandoned) in a small cupriferous quartz vein filling a fault between Pearana Basalt to the east and Carawine Dolomite to the west. Blatchford (1925) described the vein as being 0.3 to 0.4 m thick and opened up by a 3-m-deep underlay shaft from which 2 to 3 t of ore (malachite, chalcocite, and cuprite) had been extracted. A sample assayed 5.77 per cent copper and a trace of silver. The Camel Hump South prospect (20°55′50″S, 121°02′20″E) is 11 km southwest of Baramine homestead, and consists of a cupriferous quartz vein in Pearana Basalt. The vein is up to 0.6 m thick and has been costeaned for 15 m along strike; the copper carbonates are accompanied by lead carbonates (Blatchford, 1925). About 1.5 km to the north at the isolated hill known as Camel Hump there are cleaved felsic tuffs (Baramine Volcanic Member of Lewin Shale) which contain veinlets and small pods of malachite.

Wyloo Anticline Area

The Wyloo Anticline (Daniels, 1970) is close to the western edge of the Hamersley Basin and consists of a core of undifferentiated Fortescue Group metabasalt and subordinate metasedimentary rocks, containing a small inlier of Archaean rocks in the east.

Blacks (Belfrey, Metawandy) prospect (22°37′00″S, 116°18′30″E) is 11.6 km at 004 degrees from Mount De Courcey in an apparently south-dipping sequence of chert and deformed mafic to felsic metavolcanic rocks. At the prospect the chert forms a conspicuous ridge and is structurally underlain by a sheared, fine grained siliceous metavolcanic rock (pyritic in parts), which is green stained over the basal 10 m of its outcrop. An adit has been driven for 15 m towards 220 degrees into this rock, and small gougings occur adjacent to the adit. The mineralization is weak and apparently of small extent and is probably dominantly iron sulphide at depth. A small amount of ore appears to have been extracted, but there is no official record of any production. The prospect was first referred to by Maitland (1909, p. 58). About 1 km to the west a 2 m deep pit reveals a 5 to 10 cm thick quartz vein with copper-stained goethite patches. The vein parallels the south-dipping cleavage of a 1 to 2 m thick recrystallized chert in fine-grained quartz-chlorite phyllite. This chert seems to be along strike from the much thicker chert at Blacks prospect.

Mindel Well occurrence (22°33′00″S, 116°06.00″E) appears on the Wyloo Sheet (Daniels, 1970) in undifferentiated Fortescue Group rocks at the western end of the Wyloo Anticline. It has not been inspected.

Copper minerals accompany gold-bearing quartz veins at the Paulsen (22°34′30″S, 116°14′20″E) and Belvedere (22°36′50″S, 116°17′20″E) mines in metabasaltic and psammitic metasedimentary host rocks respectively. Small quantities of copper ore were produced in 1916, 1939 and 1949 (Table 24). Silver-lead mineralization also occurs at Belvedere mine (Blockley, 1971b, p. 179).

Other Occurrences

At the Glen Herring occurrence (21°20′50″S, 119°34′20″E) 28 km southwest of Marble Bar, copper staining has been noted from the Mount Roe Basalt (Hickman and Lipple, 1975).

A felsic tuff within the Hardey Sandstone near Meentheena has been reported to contain low grade copper mineralization (Hickman, 1975b).

HAMERSLEY GROUP (TYPE G)

BALFOUR DOWNS AREA

Small copper deposits have been known from the area north of Balfour Downs homestead for over 50 years, and small amounts of cupreous ore totalling 178.56 t and averaging 20.43 per cent copper were produced from 1958 to 1965. The deposits have not been inspected and available information is sketchy (Low, 1963; de la Hunty, 1964). According to de la Hunty (1964, p. 20-21) the mineralization is commonly in joints or faults in the Carawine Dolomite, near outcrops of Davis Dolerite.

None of the Balfour Downs area occurrences seems to be of economic importance. It is possible that small amounts of copper have been leached from the Davis Dolerite (which may contain minor chalcopyrite) by meteoric water and locally redeposited in solution cavities and joints in the alkaline environment of the Carawine Dolomite.

The main producing deposit appears to have been the Blowhole (Mount McLarty) prospect (22°19′10″S, 120°48′10″E) which is 6.5 km southeast of Mount Rudall (erroneously referred to as Mount McLarty by Low, 1963) and 6 km north of Saddleback Hill. Malachite, chrysocolla, cuprite, atacamite and azurite occur in seams and bunches in joints and minor shears exposed in shallow pits (up to 3 m deep) covering a 10 hectare area. A sinkhole in the dolomite is some 55 m deep, and is reported to contain a seam of malachite at 23 m depth. Five percussion drillholes totalling 178 m were drilled in the prospect area by PMI in 1969. The drillholes encountered barren, variably silicified dolomite or chert breccia (cave breccia): the mineralization is evidently very restricted in lateral extent.

The Turammunda Rock Hole prospect (ca. 22°30′30″S, 120°48′00″E) is not accurately located, but is similar in style of mineralization to the Blowhole prospect. In 1962 and 1964, 7.27 t of cupreous ore (25 per cent copper) were produced.

An occurrence 10.5 km south-southeast of the Turammunda prospect consists of a 4.6 m deep shaft sunk in dolomite on a high-grade (30 per cent copper) pod of copper mineralization less than 2 m square in area.

De la Hunty (1964, p. 20) mentions other similar occurrences located 1.6 km southeast of Coorapline Well (22°28′30″S, 120°46′40″E) and in Googhenama Creek (ca. 22°04′00″S, 121°18′00″E).

OTHER OCCURRENCES

Accessory or minor amounts of pyrite and chalcopyrite have been noted from dolerite sills of the Weeli Wolli Formation and some sections of the Woongarra Volcanics (MacLeod, 1966, p. 162-163).

WYLOO GROUP (TYPE C)

DUCK CREEK DOLOMITE

The Red Hill mine (21°52′00″S, 116°05′20″E) is 12.5 km at 013 degrees from Red Hill homestead, in a north-northwest-trending, isolated range of low hills composed largely of dolomite and chert. A laminated quartz vein 0.3 to 2.0 m wide strikes east-west for 130 m over the summit of the most westerly dolomite ridge (Fig. 23). The vein is vertical at the centre, steeply north dipping at its western end and steeply south dipping at its eastern end. In 1907, several shafts were sunk on malachite-cuprite-rich pods in the vein at the hill summit, where the dolomite is buff-coloured and has been silicified (?Tertiary profile). The vein consists of green-stained mixed quartz and goethite and marginal stockworks of quartz veinlets. Some pyrite is present in the waste dump from No. 1 shaft. Production from the mine has not been recorded, but was probably restricted to high-grade patches containing more than 15 per cent copper.

Two similar cupriferous limonite-quartz veins in dolomite are reported (Maitland 1909, p. 92-93) about 1 km north of the Red Hill mine at Beechworth prospect (21°51′30″S, 116°05′10″E) and Niven prospect (21°51′30″S 116°03′00″E). The vein at Beechworth strikes 310 degrees and dips west and was opened up by a 6 m deep shaft from which about 4 t of 30 per cent copper ore were extracted. The vein at Niven strikes west but the mineralization seems to have attracted little attention. The 'Kangaroo' lease (ML 166) is not accurately located but it is probably in one of the cupriferous quartz veins in the dolomite. Cupreous ore production totalling 47.07 t averaging 15.03 per cent copper was reported jointly with a lease at Cane Hill (see below).

Red Hill South mine (21°52′30″S, 116°05′20″E) is 1 km south of Red Hill mine, immediately west of the ridge coinciding with the main dolomite outcrop. A subvertical cupriferous limonite-quartz vein up to 40 cm thick occupies a small northeast-striking fault in bedded chert and dolomite dipping at 25 degrees to the south-southwest (Fig. 24). Copper mineralization (malachite, chrysocolla) appears to be most abundant where a dolerite sill intrudes the sequence. Production apparently took place in 1907 (about 8 t of picked ore) and 1937 (about 4 t of 50 per cent copper ore) but there are no official records of this.

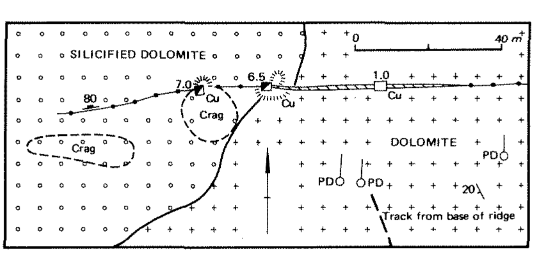


Figure 23. Surface plan of Red Hill copper mine

The Rundles Hill prospect (22°10′00″S, 116°04′40″E) is in an isolated ridge standing up from the plain, some 7 km southeast of Red Hill trigonometrical station. The ridge consists of dolomite dipping at 25 degrees to the northeast; relationships with the surrounding quartz-mica schist of the Ashburton Formation have not been clarified. A vertical quartz vein emplaced in the dolomite is 400 m long, up to 1 m wide and strikes 300 degrees. The southeastern section of the vein carries veinlets, pods and disseminations of malachite, cuprite and chalcopyrite, and a sample taken over a 1.02 m width next to a 5.5 m deep shaft assayed 1.66 per cent copper (Jones, 1939, p. 12). Shallow pits northwest of the shaft show a little copper in veinlets. The prospect is of no economic importance. A few tonnes of copper ore were raised early this century but there is no official record of production.

ASHBURTON AND CAPRICORN FORMATIONS

Small deposits in veins and shears are known from two areas. In the Red Hill station district the occurrences are cupriferous limonitic quartz veins, whereas at Ashburton Downs polymetallic mineralization is found in small veins and shear zones. Production figures are incomplete, but the Red Hill district is credited with about 223.0 t of copper ore (all from the Cane Hill mine) and 47.70 t of cupreous ore, though in this latter case returns were made jointly with mines in the dolomite north of Red Hill homestead. The Ashburton Downs district has a production record of 24.08 t of copper ore (4.14 t copper) and 244.16 t of cupreous ore averaging 13.04 per cent copper.

Doust (1975) erected an informally named volcanic unit called the 'Stuart Formation' as part of the Ashburton Formation in the Mount Stuart area. The 'Stuart Formation' consists of acid to intermediate volcanic rocks and banded iron-formation, but is apparently devoid of mineralization.

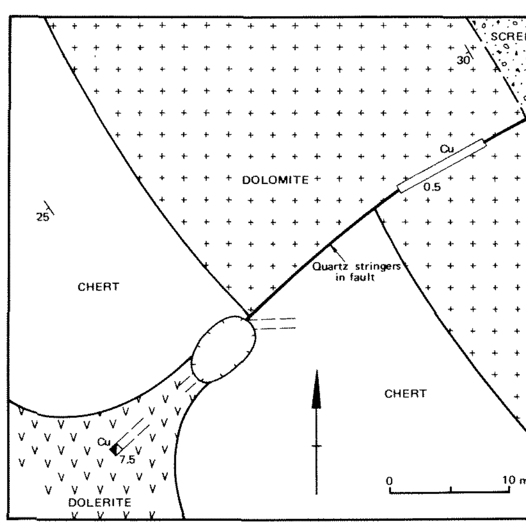


Figure 24. Surface plan of Red Hill South workings

Red Hill district

The Cane Hill (Cano, Highams) mine (22°09′30″S, 116°02′50″E) is 5 km at 178 degrees from Red Hill trigonometrical station and is incorrectly shown on the Wyloo Sheet (Daniels, 1970) 1 km north of the actual position. The country rocks are feldspathic metagreywackes, with interbedded dolomite, chert and fine-grained siliceous clastic rocks containing a cleavage sub-parallel to bedding which strikes 306 degrees and dips steeply southwest. The quartz vein has a similar orientation and is traceable for 400 m along strike being up to 2.4 m wide (Fig. 25). Veins and lenses of geothite, malachite, cuprite, chalcocite and

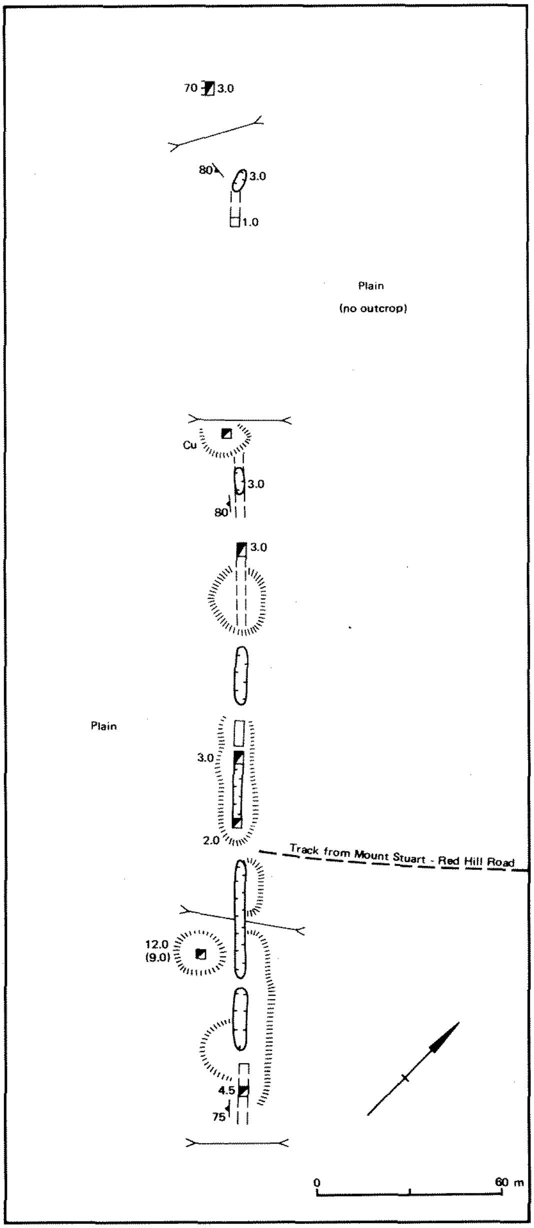


Figure 25. Surface plan of Cane Hill workings

chalcopyrite within the quartz were up to 75 cm thick. Most ore was extracted from the southern end of the workings (now collapsed) where an ore shoot 43 m long and about 0.75 m thick was mined to a depth of 12.8 m (water table). The mine produced about 44 t of copper ore (grade unrecorded) in 1899, 178.3 t of copper ore (34.39 t copper) in 1907 (ML 62) and probably a portion of the 47.70 t of cupreous ore (15.03 per cent copper) recorded jointly for the Bungarra (ML 165) and Kangaroo Leases in 1961-1962.

Material on the dumps includes dolomite, shale, chert and a fine-grained, foliated quartz-sericite rock containing quartz eyes and lenses (?felsic tuff). The host rocks may be more varied than the country rock outcrops indicate. Costeans and three shallow (about 10 m deep?) percussion drillholes were put into the vein by Great Boulder in 1973. The highest intersection was 1.52 m of 1.74 per cent copper. No material anomalous in lead or zinc was found and an induced polarization survey failed to detect any anomaly.

Lockes (Whynot) mine (22°07′10″S, 116°00′50″E) is 5.5 km northwest of Cane Hill mine in phyllite with associated limestone striking northwest (Maitland, 1909, p. 89). These rocks are probably also within the Ashburton Formation close to the basal unconformity of the Mount Minnie Group. A cupriferous quartz vein was traced for 30 m in a north-easterly direction and was prospected by an 8.5 m deep shaft, and a short drive to the northeast. Malachite, chalcocite, cuprite and limonite occurred in bunches up to 30 cm thick. There is no recorded production and the workings have collapsed. The mine was not inspected.

Some 600 m west of Lockes is the Big Blow prospect which consists of several thin cupriferous quartz veins including a 2 to 3 m thick quartz blow from which the prospect takes its name. This area appears to be along strike from a north-northwest-trending fault shown on the Wyloo Sheet. There are some shallow prospecting pits in the area.

Ashburton Downs District

The Windy Ridge (Tropic) mine (23°27′10″S, 117°15′10″E) is 24 km east-southeast of Ashburton Downs homestead and 300 m northeast of a fence line oriented east-southeast which leads to No. 22 Bore (disused) (Fig. 26). Copper ore amounting to 20.37 t (2.58 t copper) was produced in 1951 (PA's 264, 265) and cupreous ore totalling 115.36 t and averaging 17.73 per cent copper was extracted in 1951, 1960, 1961, and 1963 (PA's 264 and 323, MC's 22 and 23). Shallow pits and gougings cover a partly bulldozed area about 150 m long (east-west) and 50 m wide. These excavations are in limonite-quartz veins and pods, up to 50 cm thick but commonly less than 10 cm thick, some of which contain malachite, chrysocolla and rarer chalcocite and cuprite. These veins and pods are mainly emplaced in a slaty or fracture cleavage, striking about 290 degrees and dipping 5 to 10 degrees northwards, which is developed in pale grey-green to purple shale to slate. A bedding fissility, striking 280 degrees and dipping steeply to the north or south, produces an intersection lineation with the cleavage. Some veins are subparallel to the bedding, others are vertical and cross cutting. None of the veins seems to have any strike extent beyond a few metres. The description given by Low (1963, p. 97). suggests that an exotic cupriferous gossan was developed as a capping over the pods and veins of cupriferous limonite-quartz. This capping has now been removed. Similar small veins and pods with very minor amounts of copper occur for 1.5 km to the east in the same range of hills.

A cupriferous, limonitic quartz vein occurs at the Goobaroo Pool prospect (23°29′00″S, 117°17′36″E). The vein is reported to be parallel to the bedding which strikes northwest and dips at 30 degrees to the northeast. Some 3.31 t of cupreous ore averaging 15.91 per cent copper were produced in 1961.

Mount Blair South prospect (23°29′00″S, 117°08′00″E) is 4.5 km south of Mount Blair in low, rounded hills of cleaved pale-green (red-weathering) shale to slate. The bedding strikes about 280 to 285 degrees and dips vary between 10 and 70 degrees to the north because of open folding. An open cut 25 m long, 2 to 4 m wide and 1 to 3 m deep is oriented 295 degrees and dips steeply south parallel to a curving slaty cleavage. This excavation is in the sheared axial zone of a flexural fold. The mineralization consists of malachite-limonite veinlets in, or associated with, quartz blows, pods and veins. Fine-grained specularite occurs in some lumps of quartz. The mineralized quartz lens does not extend beyond the open cut. In 1951 and 1964, 9.71 t of copper and cupreous ore (2.70 t copper) were produced (PA's 263 and 350) and some bins of hand-picked ore remain.

The Station Creek prospect (ca. 23°26′12″S, 117°01′48″E) is reported to be 5.6 km south of Ashburton Downs homestead (Blockley 1971b, p. 187). A narrow mineralized shear has been opened up by pits and an open cut over a length of 21 m. A stockwork of cupriferous quartz veinlets extends a metre or so into the shales on the footwall side of the shear. Lead mineralization is present in the main shear.

The Soldiers Creek Northeast (Donnelly) copper-gold occurrences (23°35′30″S, 117°06′00″E) consist of malachite, chrysocolla, limonite and gold-bearing quartz veinlets emplaced along bedding, cleavage and fracture planes. The country rocks are phyllites striking east with moderate to vertical dips. The area was investigated by Anglo American in 1973. Geochemically anomalous zones 200 to 400 m long and 30 to 40 m wide were defined and costeaned. Average assay values of channel samples from the costeans were 0.43 per cent copper and 0.37 ppm gold.

An occurrence 15 km northeast of Ashburton Downs homestead produced 1.79 t of cupreous ore in 1963 averaging 23.82 per cent copper.

Another group of prospects is present some 13 km west of Ashburton Downs homestead amongst the rugged, dissected hills of the Capricorn Range. The Anticline, Casleys, Ledge and Stockyard Creek prospects are also briefly described by Blockley (1971b, p. 185-187). In 1962-1963, 128.79 t of cupreous ore averaging 8.84 per cent copper were produced from prospects in the area (MC's 25 and 26). The Anticline, Casleys and Bali High East prospects are all situated in the sheared, unconformable contact zone between the Ashburton Formation to the north and Capricorn Formation to the south. The strike is east-southeast and dips are moderate to steep, though commonly shallower in the ridge-forming arenites of the Capricorn Formation, which generally lack the well developed sub-vertical cleavage present in the shale to slate, grit, arenite and lithic metagreywacke of the valley-forming Ashburton Formation. The mineralization is copper dominated but contains minor or accessory lead, zinc, and antimony, and anomalous amounts of bismuth, uranium, silver and arsenic. Most prospects are at, or close to, the base of the Capricorn Formation, and it is possible in some cases that syngenetic mineralization has been leached from this formation and redeposited in structural sites in the underlying Ashburton Formation.

The Casleys (Bali Low, Bali Lo) prospect (23°23′50″S, 116°55′10″E) is at the western end of the sheared contact zone where the Ashburton Formation

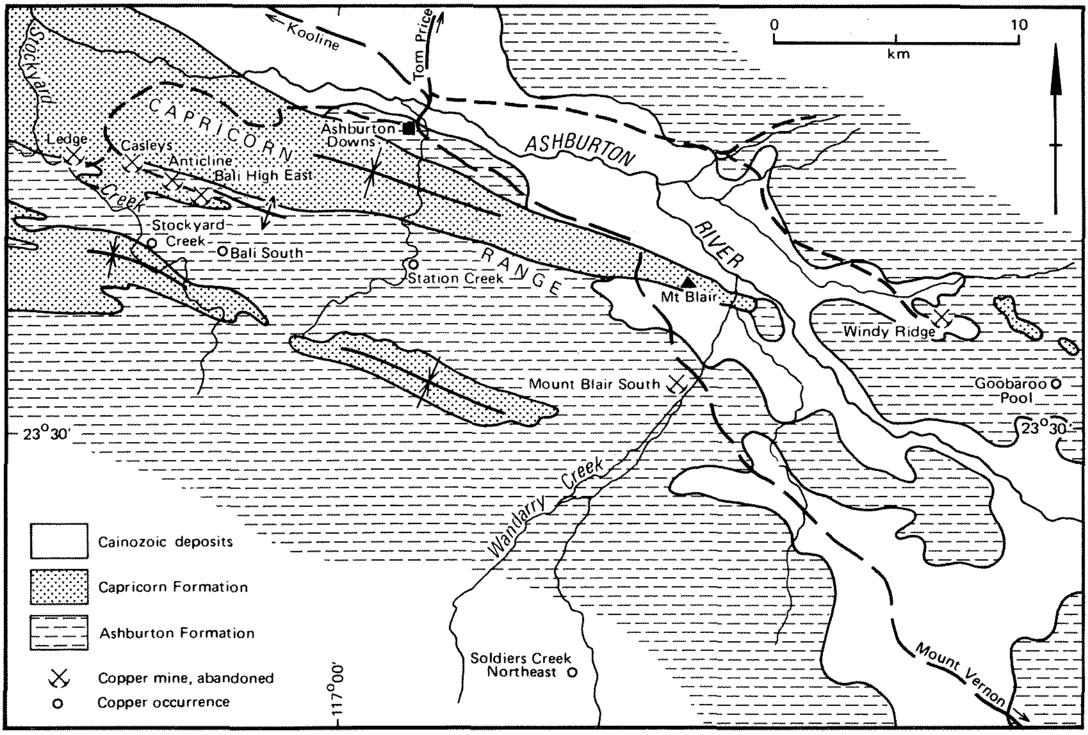


Figure 26. Copper deposits in the Ashburton Downs district

outcrop narrows westwards into the hinge of a major anticlinal fold closing in the same direction. Mineralization occurs over 240 m of strike as small pods (up to 1 m long and 50 cm wide) of limonite with disseminated malachite-azurite-chrysocolla and various copper arsenates present in a 1 to 3 m wide chloritic and brecciated zone dipping steeply south. Metazeunerite (a uraniferous copper arsenate) occurs as fracture coatings in quartzite of the Capricorn Formation, where opened up near the eastern end of the mineralized zone. A diamond drillhole collared 50 m northwest of this open cut by PMI intersected the zone at 60 m vertical depth and assayed 1.2 per cent copper over a drilled width of 2.8 m. Assays of up to 50 ppm lead, 460 ppm gold and 370 ppm nickel were yielded also. A channel sample taken by Russgar Minerals across the zone, where exposed in the open cut, assayed 1.7 per cent copper, 0.3 per cent lead, 240 ppm zinc, 6 ppm silver, 700 ppm arsenic and 100 ppm uranium oxide over 5 m. Anomalous amounts of bismuth were also detected in selected samples.

The Anticline (Bali High, Bali Hi) prospect (23°24′00″S, 116°56′00″E) is 1.2 km east-southeast of Casleys prospect. The shear zone here is 1 to 2 m wide, is sporadically mineralized for 700 m, and dips at about 50 degrees to the south. A second fracture cleavage is associated with the shear, and rocks of the Ashburton Formation are folded and boudinaged in the vicinity. The Capricorn Formation is locally upturned and brecciated at the contact. At about the centre of the green-stained mineralized zone Westfield sank a shaft, inclined at 55 degrees to the south, to a vertical depth of 29 m (34 m down dip), and put in short drives to the east and west from a crosscut put out 9 m southwards from the base of the shaft. The mineralized zone was encountered in the shaft between 12 and 24 m, and it consisted of disseminated pyrite, galena, chalcopyrite, bornite, digenite, covellite, tetrahedrite, skutterudite ($CoAs_3$) and a copper-antimony sulphide. A diamond drillhole collared by PMI 120 m west of the shaft encountered dominantly pyrrhotite at 76 m vertical depth assaying up to 300 ppm copper, 530 ppm lead and 2 600 ppm zinc over 3.9 m true width. The mineralized zone was also surface sampled by PMI at 30 m strike intervals over 1.1 m widths yielding a best result of 2.13 per cent copper, 13.5 per cent lead and 0.34 per cent zinc. Similar sampling by Russgar showed the presence of anomalous bismuth (150 ppm), uranium (200 ppm U_3O_8), silver (270 ppm) and arsenic (4.8 per cent). A small amount of cupreous ore was produced in 1961 (MC26).

The Bali High East prospect (23°24′20″S, 116°57′00″E) is 2.8 km east-southeast of Casleys prospect, and here the mineralized shear is 280 m long and 1 to 2 m wide. Malachite, azurite, chrysocolla and rare chalcocite disseminations occur sporadically in the shear which in the east is 40 m north of the unconformity. Some small pits have been dug on the shear. Surface material may assay up to 27 per cent copper with anomalous amounts of lead, zinc, bismuth, arsenic, silver and uranium.

The Ledge prospect (23°23′40″S, 116°53′40″E) is 2.8 km west of Casleys prospect on the south side of a high ridge of Capricorn Formation, and about 250 m north of Stockyard Creek. Interbedded shale, quartzite, grit, lithic greywacke and fine-grained arenite strike 285 degrees and dip at 56 degrees to the north. A weakly developed cleavage visible in the shaly units dips steeply north. The host rocks appear to be Capricorn Formation close to the basal contact with the Ashburton Formation. A siliceous shear zone 1 to 2 m wide and striking parallel to the bedding but dipping at 78 degrees to the south, has been open cut in a ledge-like fashion over a length of 50 m. High-grade pods of malachite, chrysocolla, chalcocite, tenorite, cuprite and cerussite occur with limonite and quartz as a matrix to breccia in the shear zone. The deposit contributed a small amount of high-grade cupreous ore to the production total of the area in the early 1960's.

The Stockyard Creek prospect (23°25′40″S, 116°55′10″E) may be reached by driving upstream along Stockyard Creek from the Ledge prospect. A small, pale-buff-weathering ridge of Ashburton Formation rocks immediately north of a bigger ridge of Capricorn Formation, consists of cleaved pebbly metagreywacke, conglomerate, arenite and shale to slate striking about 070 degrees and dipping steeply south. The cleavage is subparallel to the bedding. Small patches (up to 10 by 5 cm in area) of malachite staining and fracture coatings occur scattered over an outcrop area of 175 m by 50 m. There is no vein quartz associated with the mineralization which appears to be local meteoric redistribution of minor syngenetic copper (from Capricorn Formation?). An adit has been driven 15 m into the ridge from the southern side and shallow gougings are present. Surface sampling by Russgar Minerals has shown this mineralization to be anomalous in antimony and arsenic, and weakly anomalous in lead, zinc, uranium, bismuth and silver. Similar occurrences have been reported 3 km to the east.

OTHER OCCURRENCES

Minor amounts of copper minerals are present in the galena-bearing quartz veins of the Kooline lead field (23°06′S, 116°27′E) described by Blockley (1971b, p. 160-171). Lead-copper mineralization at Mount Stuart and South Hardey River is also described by Blockley (1971b, p. 188-189).

CHAPTER 11

Gascoyne Province

GEOLOGY

The Proterozoic metamorphic and igneous rocks of the Gascoyne Province occupy an area of 50 000 km² in the northwestern part of the State. The southern boundary of the province coincides with a change from the westerly strikes of the Gascoyne Province to the north-easterly strikes of the Yilgarn Block. The boundary on the Robinson Range Sheet is referred to as the Murchison Tectonic Lineament in the east and the Bedaburra Shear Zone in the west (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-northern boundary corresponds with the western limit of the Bangemall Basin, except on the Wyloo and Yarraloola Sheets where a transitional boundary with the Hamersley Basin is recognized. Permian sedimentary rocks of the Carnarvon Basin bound the province to the west.

The complexity of the Gascoyne Province is illustrated by Table 25. Regional geological study has not yet proceeded to a stage where the nature and inter-relationships of the major rock groups throughout the Province are well established. The 'older gneissic sequence' (group 1, Table 25) includes reworked Archaean gneiss and amphibolite (Robinson Range and southeastern Glenburgh Sheets), as has been suggested for the oldest rocks in the Rudall Metamorphic Complex of the Paterson Province. The relationship between the basement complex and the presumed 'cover sequence rocks' of group 2 (Table 25) is not always clear, and the status of the Mount James Beds (clastic quartzose metasedimentary rocks) in relation to the Ashburton Formation remains unresolved. Recent mapping on the Yanrey and Mount Phillips Sheets suggests that the Ashburton Formation as previously mapped on the Wyloo and Edmund Sheets includes rocks of both "basement complex" and "cover sequence" aspect.

TABLE 25. SUMMARY OF GEOLOGY AND CUPRIFEROUS MINERALIZATION OF THE GASCOYNE PROVINCE

Major rock groups and events	Mineralization and remarks
Bangemall Group or Phanerozoic cover rocks	
---------- *Unconformity* ----------	
4. Late to post-tectonic granitoid plutons, some tourmaliniferous (ca. 1 600 m.y.)	Minor copper plus silver-lead and uranium deposits in veins and shears (groups 4 and 3)
3. Deformation and low to medium-grade regional metamorphism; syntectonic granitoids, some porphyritic (ca. 1 700 m.y.)	
2. "Cover sequence" comprising—Mount James Beds metasedimentary rocks; Ashburton Formation metasedimentary rocks; unassigned psammite and semi-pelitic to pelitic schist	Minor copper plus silver-lead, zinc and gold deposits in veins and shears
---------- *Highly deformed unconformity* ----------	
1. "Older gneissic sequence" of migmatite, paragneiss, banded calc-silicate gneiss, quartzite and schist with other gneiss and amphibolite in the southeast; all metamorphosed to amphibolite-granulite facies	Minor copper plus silver-lead deposits in veins and shears

MINERALIZATION (MAINLY TYPE C)

The cupriferous mineralization discovered so far is not of great economic importance (Table 25). Total production of copper ore is 180.72 t (65.74 t copper), and of cupreous ore is 260.84 t averaging 10.91 per cent copper (Table 26). Nearly 90 per cent of the total ore produced came from the Uaroo mining centre (Yanrey Sheet) in the northern part of the province. The bulk of this mineralization appears to be within psammitic to semi-pelitic metasedimentary rocks, assignable to the "cover sequence" of group 2 (Table 25). The iron-copper-lead-zinc sulphide mineralization at Yarraloola may be a modified distal volcanogenic deposit in partly felsic volcanic metamorphic host

TABLE 26. MINE PRODUCTION OF COPPER FROM THE GASCOYNE PROVINCE

Mine or group	Copper ore and concentrates (t)	Cupreous ore and concentrates (t)	Average grade (%)	Contained copper (t)
Dalgety Downs	4.10		20.24	0.83
		8.07	9.75	0.79
Mangaroon		2.13	6.65	0.14
Minga Bore		4.22	13.60	0.57
Mooloo Downs		5.80	18.60	1.08
P.A. 322		40.27	17.73	7.14
Range Well area		15.43	23.69	3.66
Turtle		45.86	4.43	2.03
Uaroo group	17.36		25.35	4.40
		68.99	7.18	4.95
Victoria	148.34		37.85	56.13
		60.03	10.71	6.43
Weston group	10.92		40.11	4.38
		2.95	26.06	0.77
Yarraloola		2.75	14.60	0.40
Yinnietharra		4.34	11.44	0.50
Totals	180.72	260.84	[1]21.33	94.20

[1] Overall weighted average for copper and cupreous ore and concentrates combined.

rocks. This is an important indicator of a style of mineralization of potential economic interest. Mineral deposits in the granitoids or the "basement complex" are very sparse, but it will be noticed that weak polymetallic mineralization appears to have been present throughout the evolution of the province. This may indicate some degree of repeated mobilization of pre-existing metallic deposits. Several granitoid plutons in the province are weakly radioactive so the presence of uranium in some cupriferous occurrences (e.g. Mundong Well area) in the granitoid rocks is not surprising.

UAROO MINING CENTRE

UAROO GROUP

This group of workings (22°43′10″S, 115°19′10″E), discovered in 1901, is 8 km at 321 degrees from Uaroo homestead, on the eastern margin of a range of hills trending north-northwest. This direction corresponds to the regional strike of fine-grained to medium-grained psammitic to semi-pelitic metasedimentary rocks which are hosts to the mineralization. The bedding in these rocks strikes 330 to 340 degrees and dips at 70 to 80 degrees eastwards. A vertical or steeply east-dipping, sinistral cleavage strikes about 350 degrees. Subconcordant, lens-shaped quartz blows a few metres long and up to 1 m thick are widespread and are also cleaved. Concordant and discordant quartz veins are also present and are sporadically limonitic and cupriferous in a zone 4 km long and up to 700 m wide. The most productive workings appear to have been at the northern end of the mineralized zone, in an area of 300-m strike length and 40-m width, including what were formerly known as the Sunset and Pedan leases. Details of the old workings are given by Maitland (1909). Total recorded production is small (Table 26) in relation to the extent of the workings, and evidently some ore was disposed of without official returns.

Chrysocolla, malachite, atacamite, cuprite and chalcocite occur in bunches and veinlets with goethite and hematite in quartz veins 5 to 100 cm thick. Most veins parallel the bedding, but some are cross cutting, and some pods of rich ore occur at the intersections of concordant and discordant veins. There is no discernible wall-rock alteration. Northeast-trending faults offset the quartz veins. The ore contains small amounts of lead, silver and gold, as exemplified by a parcel of ore from the Pedan lease which assayed 20.33 per cent copper, 63 g/t silver and 6.3 g/t gold (Maitland 1909, p. 69). In 1964 Westfield carried out 605 m of percussion drilling (terminal depth 33 to 38 m) at the northern end of the mineralized zone (Sunset lease). The best values obtained were 1.5 m drilled width assaying 1.75 per cent copper, 3.05 m assaying 0.90 per cent copper and 6.10 m assaying 0.98 per cent copper. Correlation of mineralized intersections from drillhole to drillhole was generally not feasible and no pattern to the mineralization emerged. The deeper holes encountered fresh quartz-chlorite-sericite phyllite.

VICTORIA COPPER MINE

This mine (22°42′30″S, 115°11′20″E), discovered around 1914, is 5.3 km at 345 degrees from Deep Well (on the Northwest Coastal Highway), and is the largest single copper producer in the province (Table 26). The workings exploited quartz-carbonate-goethite-malachite-azurite-bearing veins emplaced subparallel to the foliation in siliceous quartz-muscovite-chlorite schist striking 340 degrees and dipping westwards. The quartz veins and lenses are foliated and lineated (down dip mineral lineation) like the host rocks. The productive section of the workings is about 70 m long with openings 1 to 2 m wide. The main shaft is now 12 m deep and dry, but was formerly 21 m deep and serviced drives at 18.3 m, 12.2 m and 6.1 m depths. The reported grades suggest that there was substantial supergene enrichment in the deeper levels, and Simpson (1952, p. 162) mentions that a malachite-cuprite sample assayed 40.3 per cent copper. Some percussion drilling and shallow costeaning has been done at the northern end of the workings.

WESTON GROUP

The Weston (Valentine, Walgo) mine (22°46′50″S, 115°16′10″E) is 17.2 km at 162 degrees from Deep Well, in a belt of quartz-mica-chlorite phyllite to schist striking north-northwest and dipping steeply west (Nyang Range). A series of thin, sub-concordant quartz veins and shears occupies an area about 700 m long and 120 m wide forming the summit of a low, rough ridge. The cupriferous part of this area is only about 12 m wide and has been exploited by two open cuts 75 m apart. The northern open cut is 10 m long, 3 m wide and 4 m deep, whereas the southern open cut is 36 m long, averages 3 m wide and 3 m deep, and contains two shafts originally sunk to 27.4 and 11.3 m depth (water at 24.4 m). Channel sampling in these openings by Finucane and Sullivan (1939b) indicated average values less than 0.5 per cent copper over 1 to 2-m widths with some higher grade patches (e.g. north-western wall of northern open cut) assaying 5 to 6 per cent copper over 4.8 m. Copper carbonates and oxides, and chalcocite comprise the known mineralization.

The Proctor Gully prospect is 1.5 km southeast of Weston in the same country rocks, and is a similar type of occurrence. Several pits, shallow open cuts and shafts have been dug, but there appears to be no mineralization of importance present.

The Euro workings are reported to be 11 km north of Weston but are probably that distance north-northwest of Weston in the same phyllite-schist unit forming Nyang Range. The style of mineralization is again similar to Weston and occurs within a 400 m long and up to 15-m-wide zone. Low-grade malachite-azurite-chalcocite mineralization has been opened up in a 15-m-deep shaft and many small pits and open cuts.

Although not included in the production total for the Weston group (Table 26), P.A. 322 (ca. 23°01′50″S, 115°23′20″E) may be in the same semi-pelitic rock unit along strike to the south-southeast on the northern edge of the Winning Pool Sheet. No further details are available, except that the 40 t of cupreous ore was produced in 1960.

OTHER PROSPECTS

At the Bullajacka Well prospect (22°36′20″S, 115°16′20″E), which is 18.5 km at 022 degrees from Deep Well, shallow excavations have been dug on a small cupriferous quartz vein in pelitic schist. A few tonnes of ore have been extracted but there is no official record of this.

The Hornet Well prospect (22°51′30″S, 115°25′20″E) is 5 km southeast of Hornet Well, on a north-striking, sheared sub-vertical contact between fine-grained to medium-grained psammitic and semipelitic metasedimentary rocks. A network of sporadically cupriferous quartz veinlets occurs in the sheared contact and has been prospected by a 10.5-m-deep shaft, an adjoining shallow open cut 5 m long and a pit on an east-west striking cross shear. Malachite and cuprite are mainly found in the psammite. The mineralization is weak and of no significant extent as exposed.

REMAINING DEPOSITS IN METAMORPHIC ROCKS.

This section excludes silver-lead mineralization with subordinate copper minerals: these are dealt with briefly under the heading, silver-lead-copper mineralization, below. The occurrences are described from north to south.

YARRALOOLA COPPER-LEAD-ZINC PROSPECT

Yarraloola prospect (21°35′40″S, 115°55′50″E) is 6.9 km at 135 degrees from Yarraloola homestead, on the north bank of the Robe River. The prospect occurs in a small, low ridge oriented north-northeast which is dominated by two 1 to 5 m wide zones of northeast-striking and northwest-dipping (about 40-75 degrees) silicified, ferruginous, foliated caprock. Pyrite casts are present in this rock. Drilling has shown that these zones of caprock are developed over siliceous, disseminated-massive iron sulphides. The two zones appear to coalesce northwards into a crag 10 m high and 15 m wide (Fig. 27). The country rock is red weathering, sporadically pyritic, quartz-feldspar-mica-chlorite schist containing lenses and interlacing veinlets of quartz culminating in the silicified zones described. Thin cherty horizons are present in the schist, which has been assigned to the Ashburton Formation. Two old shafts in the eastern zone penetrated malachite-stained country rock and thin intervals of limonite-quartz. There is a conspicuous rarity of copper staining in outcrop in which the best mineralized area is in the southern part of the eastern zone and is up to 20 m wide and 150 m long. It consists of 1 to 5 cm thick limonite-quartz lenses and veins with some pods 1 to 5 m long and up to 50 cm thick. Apart from a few tonnes of cupreous ore produced in 1963 there is no other recorded production, although a small amount of ore was raised earlier (Jones, 1939) and the prospect was reported on by Maitland (1909).

Great Boulder investigated the prospect from 1970 to 1973 and bored ten vertical and inclined diamond drillholes—totalling 2 089 m—collared northwest of the ridge. The eastern zone was also investigated at shallow depth by 285 m of—mainly—inclined percussion drilling. The total drilling programme indicated a mineralized body 100 m long and up to 13 m wide to a vertical depth of 250 m. The best intersections obtained were a 23.78 m drilled width assaying 0.75 per cent copper, 0.51 per cent lead, 0.41 per cent zinc, and 20.1g/t silver, and 13.0 m averaging 1.92 per cent zinc, 0.89 per cent lead, 0.67 per cent copper and 28g/t silver. The best copper intersection was 6.7 m assaying 1.08 per cent copper. Average grades for all drillhole intersections are much lower than these figures. Sections of drill core from 5 cm to 14 m thick consist of 50 to 75 per cent fine-grained to medium-grained sulphides with pyrite (cobalt-bearing) being overwhelmingly dominant and accompanied by chalcopyrite, iron-bearing sphalerite and galena (Appendix 1). The gangue is quartz, variably silicified schist inclusions, and carbonate. Deformation and recrystallization generally preclude identification of primary textures in sulphides and fresh rocks, but some flattened quartz-feldspar-chlorite breccias may be pyroclastic. Thin horizons of metabasalt-metadolerite, quartz-feldspar porphyry and meta dacite have been reported in drill core, and a ridge of banded iron-formation containing north-plunging folds occurs 500 m to the south-southeast.

It seems feasible from the above data that the original mineralization formed in a distal volcanogenic setting in a sedimentary (party volcaniclastic) sequence of chert, basalt and felsic pyroclastic intercalations. The indicated size and grade of the deposit is insufficient to be of economic interest, but the prospect is important as an example of modified and partly remobilized, probable volcanogenic copper-lead-zinc mineralization in cover sequence rocks. Cupriferous quartz veins and gossans have been reported from Proterozoic rocks outcropping to the southwest.

TURTLE COPPER-LEAD MINE

Turtle mine (22°11′40″S, 115°24′30″E) is 7.5 km north of Range homestead, in quartz-feldspar gneiss on the western margin of a small body of foliated porphyritic adamellite. In 1962, 45.8 t of cupreous ore

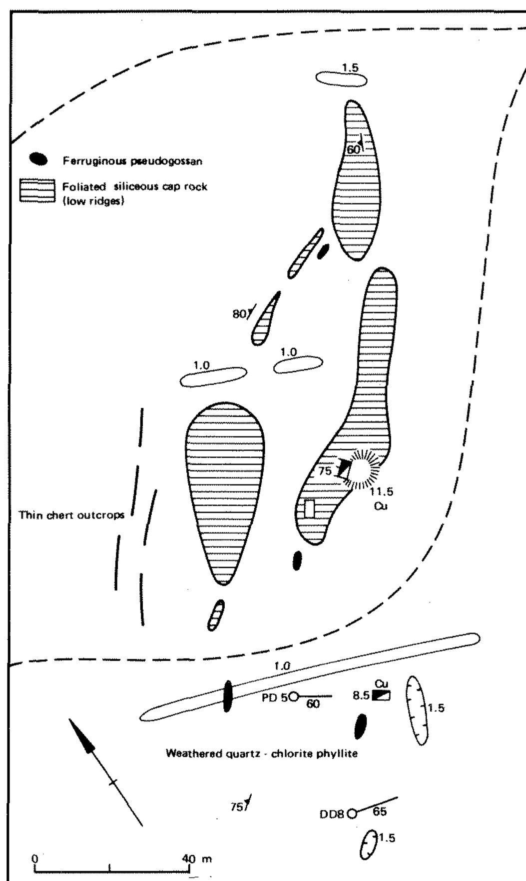


Figure 27. Yarraloola copper-lead-zinc prospect

averaging 4.43 per cent copper were produced. This ore contained some lead. Malachite, cuprite and cerussite are disseminated in ferruginous quartz lenses in a hydrothermal quartz stockwork 210 m long and up to 30 m wide, which strikes northeast and dips steeply east (Blockley, 1971b, p.178). The northeastern section of this stockwork contains the best mineralization, a shallow open cut and an 8.2 m deep shaft have been excavated here. In 1964, Westfield drilled eighteen percussion drillholes into the mineralized zone. Only two drillholes were successful in yielding mineralization of interest. Drillhole 15, sunk beneath the open cut, returned a true width of 2.4 m assaying 3.7 per cent copper within a larger intersection of 12 m assaying 4.6 per cent lead and 121 g/t silver. In another drillhole two narrow sections assayed 11.0 per cent copper with a larger intersection of 3 m true width assaying 2.45 per cent lead. The locality has not been inspected but the deposit does not appear to be of economic importance.

RANGE WELL EAST PROSPECT AND AREA

This prospect (22°22′10″S, 115°32′30″E) is 1.8 km east of the Northwest Coastal Highway, and due east of a gap in hogsback ridges formed by chert in gently undulating, poorly exposed ground. The country rocks are fine-grained to medium-grained quartz-muscovite-chlorite schist containing a subvertical cleavage, striking 020 degrees, and a steeply north-northwest-plunging mineral lineation. Lenses of pyritic, biotite and/or dark amphibole-bearing quartzite occur in the schist. Cupriferous limonitic quartz veins and lenses strike 350 degrees, are vertical, and reach 15 cm in thickness. Chrysocolla-, malachite- and chalcocite-bearing material has been dug from a small gouging in one mineralized lens.

In 1962 0.56 t of cupreous ore averaging 20 per cent was produced from PA 336 which is not accurately located, but may be this prospect. In 1963, 15.11 t of cupreous ore averaging 23.97 per cent was produced from ML 168. The location of this tenement is southeast of Range Well prospect at about latitude 22°24′30″S and longitude 115°36′00″E. Another occurrence (22°28′20″S, 115°31′50″E) of chalcocite, chrysocolla and malachite has been reported 11.5 km south of the Range Well prospect, in a shear in the Mudong Member of the Ashburton Formation.

MEILGA COPPER-GOLD PROSPECT

Meilga (Mount Agnes) prospect (22°46′10″S, 115°54′30″E) occurs in a small 15 m high hill of Ashburton Formation metasedimentary rocks 1 km east of a granitoid intrusion. A shallow prospecting shaft and adit are present on the north side of the hill. A very thin cupriferous "bed" of malachite and atacamite stained quartz-mica-chlorite phyllite to schist is intensely folded and contains average copper assays up to 1 per cent. Supergene enrichment and possible mobilization during folding and metamorphism has resulted in higher grade patches of mineralization assaying up to around 20 per cent copper, but only over a thickness of about 20 cm. Visible copper mineralization extends over 30 m east-west (strike) and a width of 15 m. Sporadic gold values up to 25 g/t have been found in the cupriferous bed. Wilson (1924) mentioned cupriferous quartz veins and shears to the west and northwest, closer to the granitoid pluton.

MINGA BORE PROSPECT

Minga Bore prospect (22°55′50″S, 116°03′00″E) is 7 km east of Glen Florrie homestead, in semi-pelitic schist of the Ashburton Formation. No details of the prospect are available, but a production of 4.22 t of cupreous ore averaging 13.60 per cent copper was recorded for 1964 (MC 60). It is likely that the mineralization consists of small, medium to high-grade pods in a cupriferous limonitic quartz vein or shear.

YINNIETHARRA DISTRICT

In 1964 and 1967, a total production of 4.34 t of cupreous ore averaging 11.44 per cent copper was reported from Crown lands in this district. Details of the location and geology of the source deposits are lacking.

MOOLOO DOWNS PROSPECT

Copper mineralization at this prospect (24°55′10″S, 116°10′20″E) occurs in faulted and sheared quartzite within an assemblage of paragneiss, migmatite and quartz-mica schist. The quartzite and the regional foliation dip steeply southwards. Copper silicates, carbonates and oxides occur as disseminations in fractures on the hanging wall side of a faulted zone marked by vuggy quartz veinlets.

Visible copper mineralization is present in a zone about 100 m long and up to 3 m wide, and has been opened up by narrow open cuts, costeans and pits. The prospect coincides with PA 62, which has a recorded production for 1963 of 5.08 t of cupreous ore averaging 18.60 per cent copper. A similar occurrence is located at latitude 24°56′40″S, longitude 115°45′40″E.

ARTHUR RIVER PROSPECT

The prospect (24°50′S, 115°40′E) occurs in layered metamorphic rocks striking about 110 degrees. Pyritic metasedimentary rocks are prominent near the prospect. The host rock is a 12 to 18-m-thick felsic schist exposed for 1.6 km of strike. The copper mineralization is found in a brecciated portion which is 45 m long. Selected fractures carrying secondary copper minerals have been opened up in shallow pits.

DALGETY DOWNS PROSPECT

This prospect (about 25°19′00″S, 116°14′30″E) is not precisely located, but is about 5.5 km southeast of Dalgety Downs homestead. The country rocks are quartzite, schist, marble and migmatite. The mineralization is apparently the result of supergene redeposition (Simpson, 1952, p. 166). A small amount of copper and cupreous ore was produced in 1953 (Table 26). A similar occurrence in quartzite is known 10 km southwest of the homestead (25°20′50″S, 116°08′20″E).

OTHER OCCURRENCES

These occurrences were discovered during recent mapping on the Glenburgh Sheet. They all appear to be of a minor nature.

1. 25°05′30″S, 116°01′00″E: malachite and chrysocolla in vein quartz within orthogneiss to migmatite.
2. 25°01′30″S, 116°06′30″E: malachite in lineated quartz veins, vertical and striking 080 degrees. Host rocks are similar to the first occurrence.

3. 25°04′20″S, 116°04′30″E: traces of malachite in north-striking pink to white barite veins, which also contain purple fluorite. The host rock is a gneissic adamellite.

4. 25°03′00″S, 116°08′40″E: specks of malachite and chalcopyrite in a steeply north-dipping quartz blow. The host rock is a paragneiss to migmatite.

DEPOSITS IN GRANITOID ROCKS

At Claypan Well (22°09′30″S, 115°28′30″E) a cupriferous quartz vein occurs in a foliated porphyritic adamellite. The occurrence is 1 km southeast of the well itself.

The Coppermine Bore occurrence (22°23′S, 115°53′E) is in the northern part of a foliated granitoid intrusion south of Mount Amy.

The Mundong Well uranium-lead prospects (23°06′50″S, 115°35′00″E), 3.5 to 4.5 km north of the well, contain small amounts of secondary copper minerals (malachite, chrysocolla). The mineralization is found in short, curving shear zones cutting muscovite-bearing pegmatitic leucogranite which contains xenoliths and rafts of semi-pelitic and amphibolitic gneiss. Foliated quartz fills the shears, and contains pockets and 1 to 10 cm-thick layers of goethite with impersistent, weak copper staining. The largest vein deposit appears to be no more than 150 m long and is only exceptionally more than 1 m wide, and has been opened up to 3.5 m depth. An old dump of copper-stained pseudogossan nearby suggests that an old prospect was sited here. The gossan was apparently developed on a granite or pegmatite contact.

At the Walker copper prospect (23°10′40″S, 115°37′00″E), located 5 km at 137 degrees from Mundong Well, schistose and gneissic rocks form a north-northwest oriented raft 100 m by 20 m in area, which is enclosed by tourmaliniferous, pegmatitic muscovite granite. A shallow open cut and a 3 m-deep costean expose very small and thin, copper-stained goethite and malachite-chrysocolla layers developed at gneiss-granite or gneiss-pegmatite contacts. Biotite-chlorite schist and massive magnetite layers may also develop at these contacts presumably as a result of metasomatic reaction. Evidently most of what would have been a few tonnes of hand-picked copper ore has been removed, though there is no record of this. It is possible that the mineralization at Mundong Well represents the type present here, redeposited by siliceous hydrothermal, solutions into narrow shear fractures.

Ti-Tree Well prospect (24°21′S, 116°06′E) consists of pervasive disseminated pyrite with minor to accessory chalcopyrite, molybdenite and galena in an epidotized biotite granitoid where cut by intersecting east to east-southeast striking shear zones.

Secondary copper minerals occur in small amounts in a 1.25 m wide silicified vertical shear zone in kaolinized granitoid rocks at Kingfisher prospect (24°54′20″S, 116°03′00″E).

SILVER-LEAD-COPPER MINERALIZATION

Several of the small silver-lead mines in the Uaroo area contain minor amounts of copper. These are the Range (22°12′S, 115°25′E), Nanutarra (22°41′S, 115°33′E), Uaroo or Silver King (22°46′S, 115°22′E) and Emu (22°47′S, 115°23′E) mines, which are described by Blockley (1971b). The mineralization is in quartz veins or shears in gneiss, amphibolite, schist, psammitic metasedimentary rock or granitoid.

Farther south at the Mangaroon lead-copper mine (23°51′30″S, 115°45′40″E) gently dipping, thin quartz veins, emplaced into quartz-feldspar-biotite gneiss, contain minor amounts of chrysocolla, azurite and malachite in addition to pyrite, galena, gold and silver (Blockley, 1971b, p. 191). In 1958, 2.13 t of cupreous ore averaging 6.65 per cent copper was gouged from a small open cut.

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CHAPTER 12

Bangemall Basin

GEOLOGY

The Bangemall Basin is a Middle Proterozoic sedimentary basin about 900 to 1 200 m.y. old, containing folded, faulted and, in places weakly metamorphosed rocks of the Bangemall Group. A summary of stratigraphy and mineralization is given in Table 27. The basin occupies an area of some 115 000 km² in the northwestern part of the State, and unconformably overlies the older Precambrian rocks of the Paterson Province, Hamersley Basin, Sylvania Dome, Gascoyne Province, Yilgarn Block and Nabberu Basin. Phanerozoic rocks of the Officer Basin terminate the outcrop of the basin to the east.

Brakel and Muhling (1976) recognize a regional facies change in the central part of the basin between longitude 118°30′′E, and 119°00′′E, resulting in an easterly lensing out of dolomite, chert and sandstone units, though shale and siltstone beds persist. Conglomerate lenses are present low in the sequence throughout the basin. This facies change partly corresponds with a major northeast-trending zone of faulting and basement arches termed the Tangadee Lineament. In the far eastern part of the basin dolomite is again present (Williams and others, 1976, p. 82). Basic sills and dykes are common but the only confirmed felsic volcanic rock is found in six small rhyolite lava domes or plugs occurring in the central part of the basin on the Tangadee Lineament (Gee and others, 1976).

TABLE 27. GENERALIZED STRATIGRAPHY AND CUPRIFEROUS MINERALIZATION OF THE BANGEMALL BASIN

Formation		Mineralization and Remarks
Western Facies	*Eastern Facies*	
Kurabuka Formation[1]	Ilgarari Formation[1]	1. Cupriferous quartz and/or limonitic fault fillings.
Mount Vernon Sandstone	Calyie Sandstone	
Fords Creek Shale[2]		
Coodardoo Formation		2. Cupriferous limonitic quartz veins and shears.
Curran Formation		
Ullawarra Formation[3]		
Devil Creek Formation[3]	Backdoor Formation[2] (Fords Creek Shale to Jillawarra Formation)	3. Pyritic beds present, rare small copper occurrences.
Discovery Chert[4]		
Jillawarra Formation[4]		4. Regionally anomalous in zinc, lead and copper in pyritic shale members.
Kiangi Creek Formation[4]	Coobarra Formation	
Irregully Formation		Dolomite, shale and mudstone; locally pyritic, minor Pb-Cu in quartz veins.
Mount Augustus Sandstone		
Tringadee Formation		
Top Camp Dolomite	Basal sequence developed along the central, northern margin of the basin.	
Northeastern Facies		
McFadden Sandstone	Isolated copper occurrence in intrusive dolerite	
Skates Hills Formation	Conglomerate, sandstone, shale, dolomite.	

MINERALIZATION

Copper mineralization of economic importance appears to be restricted to a narrow north-south oriented zone in the centre of the basin, falling within rocks of the eastern facies (Table 27). More specifically in this zone there are only two major producing centres: at Ilgarari and 40 km south at Kumarina. These centres have accounted for nearly 98 per cent of the total production from the basin (Table 28) of 2 502.34 t of copper ore (793.00 t copper) and 3 579.85 t of cupreous ore (averaging 17.06 per cent copper). The deposits exploited at Ilgarari and Kumarina are deep supergene enrichments of sulphide-quartz fault and fissure fillings, commonly sited at northeast-striking contacts between shale and dolerite. The primary source of the copper is not apparent, and though it is feasible that copper has been leached out of (or expelled from) dolerite intruded into the sequence, there is no direct evidence of this. Black shales in the sequence are weakly anomalous in copper.

Beds of several formations of the western facies are pyritic and carbonaceous, and some of these beds are regionally anomalous in zinc and to a lesser degree in lead and copper (Table 27). Black shales at the base of the Discovery Chert, and the Glen Ross Shale Member (Kiangi Creek Formation) are two examples.

TABLE 28. MINE PRODUCTION OF COPPER FROM THE BANGEMALL BASIN

Mine	Copper ore and concentrates (t)	Cupreous ore and concentrates (t)	Average grade (%)	Contained copper (t)
Bulloo Downs area[1]	79.87		25.98	20.75
Butcher Bird	37.39		22.63	8.46
Koode Magi		13.72	12.73	1.75
Towers Find	2.03		40.39	0.82
Ilgarari group	1 907.70		30.76	586.86
		1 252.81	16.19	202.82
Kumarina group	475.35		37.00	176.11
		2 302.62	17.51	403.19
Mulgul		10.70	20.70	2.22
Totals	2 502.34	3 579.85	[2]23.02	1 402.98

1. Official production returns are incomplete
2. Overall weighted average for copper and cupreous ore and concentrates combined.

Mineralization of economic interest has not been found in this environment despite extensive exploration. The base metal geochemistry of these black shales does not appear to be exceptional compared with that of black shales in general.

CUPRIFEROUS QUARTZ VEINS AND SHEARS (TYPE C)

ILGARARI GROUP

The Ilgarari workings are 2.5 km southwest of Ilgarari outcamp, and are some 16 km distant from the Great Northern Highway by a graded road heading northwest. Two groups of mine workings, called informally Ilgarari Main (24°22′00″S, 119°33′30″E) also known as "West mine", and Ilgarari Northeast (24°21′40″S, 119°34′10″E) also known as "East" or "Alac mine", are about 1.3 km apart on an east-northeast oriented line in a featureless, sparsely timbered outwash plain. This line forms a conspicuous photolineament traceable for 8 km, and anomalous in terms of surface geochemistry over a 5-km strike length. The photolineament corresponds with a fault.

With respect to contained copper, the Ilgarari Northeast workings have accounted for nearly 70 per cent of the total copper ore and 57 per cent of total cupreous ore production from the group. These workings (Fig. 28) are entirely underground (extending below the water table at about 11 m) and were operated from 1965 to 1973 during which 528.47 t of cupreous ore (27.00 per cent copper) and 1 381.51 t of copper ore (404.99 t copper) were produced from MC 97P. The Ilgarari Main workings (Fig. 29) date from 1913 and are mainly above the water table (about 14 m deep) although recent development at the northeastern end gave access to deeper levels. Production has been mostly from MC64P and had amounted to 724.34 t of cupreous ore (12.08 per cent copper) and 526.19 t of copper ore (181.87 t copper), with the last returns being made in 1970.

The country rocks are gently north-dipping to horizontal, grey (white-weathering) laminated siltstone, sandstone and shale of the Ilgarari Formation, which contains carbonaceous horizons with laminae, grains and veinlets of pyrite. The carbonaceous horizons are 1.5 to 8.0 m thick and are geochemically anomalous in zinc (up to 5 000 ppm), copper and lead (each up to 300 ppm). The sedimentary rocks are intruded and marginally baked by dykes and sills of medium-grained dolerite containing accessory pyrite. There is very little outcrop in the area except for,

(i) low outcrops of ferruginized shale cut by subvertical, copper anomalous, limonite-filled shears striking at 060 to 070 degrees, and

(ii) weathered rock exposed in costeans and open cuts (Fig. 29).

Copper mineralization is located in east-north east-striking and steeply south-dipping *en echelon* faults and shears, which are commonly developed at or near dolerite-shale contacts. Such mineralized faults have been worked over a 650 m length at Ilgarari Main (Fig. 29) and 150 m at Ilgarari Northeast (Fig. 28). The faults are open and vuggy in parts and appear to be mainly normal faults down throwing to the southeast as indicated by drag of the shale. In the two costeans at Ilgarari Main it appears that thin dolerite dykes may have been emplaced into faults. Small cross faults offset these mineralized faults locally and may themselves contain mineralization. In the northern transverse open cut at Ilgarari Main 0.1 cm to 3-cm-thick seams of fine-grained chalcocite, cuprite, azurite and malachite spread up to 25 m, from a 5 to 20-cm-thick steeply dipping vein, into the bedding of the shale. The common style of mineralization is probably represented in the costean at the northern end of Ilgarari Main. Here, six zones of limonitic veinlets and limonitic shale-dolerite mixture occur over a 10 m width, and are individually an average of 1 to 10 cm thick, and exceptionally 1 m thick. Larger pods of mineralization probably occur where faults divide, intersect or curve. Material on dumps from such zones also contains chrysocolla, malachite, cuprite, chalcocite and tenorite in veinlets, and massive, fine-grained

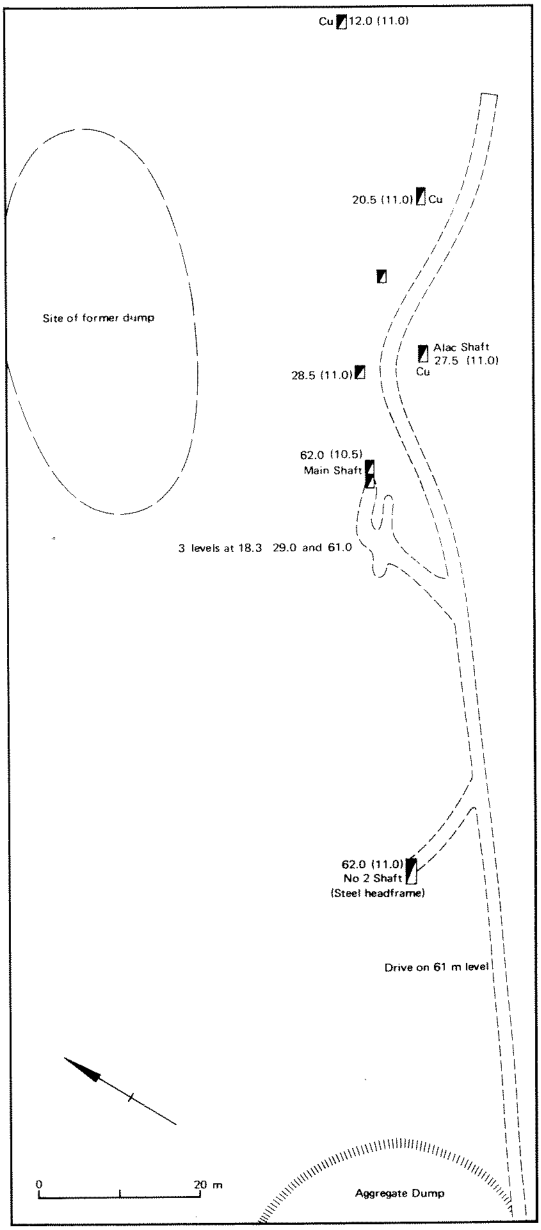


Figure 28. Plan of surface workings and 61 m level at Ilgarari Main mine

to medium-grained blocks. The paucity of vein quartz is a notable feature of the mineralization. The wall rocks are commonly partly bleached (kaolinized) and more rarely are silicified. This alteration may be only caused by surface meteoric groundwater.

Subsurface data indicate the following ore mineral zonation:

(i) 0 to 12 m—malachite, azurite, chrysocolla, cuprite, chalcocite;

(ii) 12 to 38 m—as for (i) plus more abundant cuprite and chalcocite and minor native copper; and

(iii) 38 to 130 m—chalcocite and sparse chalcopyrite.

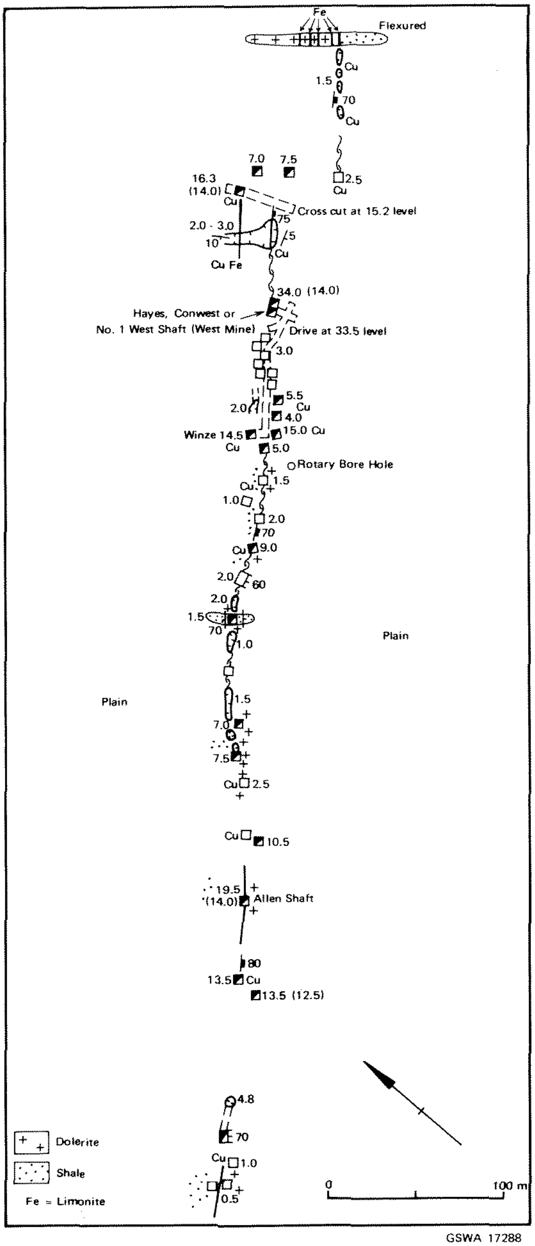


Figure 29. Plan of surface workings and 33.5 m level at Ilgarari Northeast mine

In 1967, Conwest carried out surface geochemical and induced polarization surveys along and between the lines of mineralization at Ilgarari, based on 120-m spaced traverses. Seventy-four inclined percussion drillholes averaging 43 m in length were drilled in geochemically anomalous areas, 1 150 and 360 m long, which were located at Ilgarari Main and Ilgarari Northeast respectively; the intervening area was not tested subsurface. Recovery was poor from the mineralized zones because of the open and leached nature of the faults and because of ground water inflow. Drilling was entirely in the oxidized-supergene or assemblage, and the best intersections were true widths of 16.76 m of 2.44 per cent copper at Ilgarari Main and 4.57 m of 7.15 per cent copper at Ilgarari Northeast. Two inclined diamond drillholes sited to intersect the mineralized fault 100 m northeast of Allen Shaft at Ilgarari Main (Fig. 29) encountered 1.68 m (true width) assaying 2.44 per cent copper at a vertical depth of 50 m (hole 75), and dolerite only at a vertical depth of 120 m (hole 76).

In 1968, Conwest sank the "Alac Shaft" at Ilgarari Northeast to 29 m and extracted bulk samples from the 18.3 m level which averaged 8.5 per cent copper. At Ilgarari Main, shafts were sunk to 18.9 m at the "Allen" and "Conwest" sites. A crosscut at the 18.3 m level in the Conwest shaft averaged 5.3 per cent copper over 1.8 m. Subsequently, Group Explorations extended and deepened these underground workings, and produced medium-grade to high-grade copper ore and concentrates from Ilgarari Northeast until 1973. Two shafts 62 m deep were put in at Ilgarari Northeast, and levels were driven at 18.3, 29.0 and 61.0 m; development on these levels totalled about 370 m. This development was all in one ore shoot ("A vein") within oxidized-supergene mineralization. In one small section the ore grade in a stope above the 29.0 m level was 55 per cent copper, elsewhere above this level the average grade was 5.3 per cent copper. Between the 29.0 and 61.0 m levels the average tenor was 9 per cent copper. The last development at the southwest end of the 61.0 m level encountered a 41.8 m strike length of ore averaging 7 per cent copper over 1.2 m width, and a 5.5 m length averaging about 25 per cent copper over a 1.5 m width. Plans to sink a new shaft to the southwest and establish a new level at 107 m did not eventuate.

At the Ilgarari Main workings, Group Explorations deepened the Conwest shaft to 34.0 m, and established a level at 33.5 m which was driven southwestwards for 87 m (Fig. 29). Some high-grade chalcocite ore was found, which may relate to a 6.1 m (true width) intersection of chalcocite ore averaging 43.8 per cent copper, encountered in a rotary borehole at 49 to 64 m vertical depth. This borehole was collared 95 m southwest of the Conwest shaft, and it was stopped in high-grade ore. Group Explorations recognized five "veins" in the Ilgarari Main area and proposed sinking a new main shaft southwest of the drive and establishing a 76 m level. Ore was categorized into high (25 per cent), medium (6 per cent) and low grade (3 per cent). It was also proposed to develop an 18 m deep, 9 m wide and 730 m long open pit on the low-grade ore here.

The main obstacles to continued small-scale mining here in the early 1970's were a lack of capital, an inadequate concentrating plant and the absence of planned exploratory or development diamond drilling from the surface or underground. Although it is evident from previous mining that small tonnages of medium to high-grade ore remain in existing workings, there is ample scope for exploration drilling at depth of the supergene mineralization potential in and between existing workings, and along strike for several kilometres to the west-southwest. The deep supergene enrichment present has obviously developed when the water table was perhaps 120 m or more deeper than it is today (10 to 14 m). Contrary to suppositions made by Group Explorations, it is most unlikely that the primary iron-copper sulphide ore would average more than 2 per cent copper. The remote location probably demands that sufficient high-grade chalcocite-cuprite ore be found and treated by an efficient concentrating plant on site.

KUMARINA GROUP

Discoveries of copper at Kumarina were made in 1913, about the same time that the Ilgarari copper deposits were found. Kumarina copper mine (24°41′20″S, 119°32′10″E) is 8 km west-northwest of the Kumarina Hotel (on the Great Northern Highway), and it has accounted for the overwhelming majority of the production from the group (Table 28), although separate returns for other small workings in the area have evidently not been made. These workings are mainly to the north of the mine (Fig. 30) and include Kumarina North show (1.2 km north-northeast), Rinaldi mine (2 km northeast), Kumarina Northeast show (2.4 km northeast) and Kumarina Open Cut (240 m south). All are located on small faults or shears striking 015 to 050 degrees and subvertical or dipping steeply to the northwest. Secondary copper minerals accompany limonite and hydrothermal quartz as a fault breccia matrix, or as thin veins, pods and veinlets in the fracture zone. The country rocks are thinly bedded shale, arenite and siltstone of the Backdoor Formation which dip gently to the north, but are only poorly exposed in gently undulating terrain. In common with Ilgarari, dolerites intrusive into the sedimentary rocks have exercised at least some structural control on mineralization because most veins or lodes are found at or near dolerite contacts.

The workings at Kumarina copper mine are entirely underground and extend for some 200 m at 000 to 015 degrees, although the deeper workings (to 48.8 m depth) are about 100 m long and are largely north of the main shaft (Fig. 31). The mineralization comprises chrysocolla, malachite, cuprite and chalcocite in a kaolinized fault breccia cemented by milky quartz, with chalcocite occurring down to about the limit of the underground workings at 49 m depth (35 m below the water table). At this depth the mineralized zone is only 0.6 m wide, but nearer the surface widths up to 4.6 m existed. However the strike length of the shoot increased with depth from 7.6 m at the surface to 100 m at depth. A drillhole put in by Carpentaria in 1962 intersected a drilled width of 6.7 m of mineralization at 30 m vertical depth, which assayed 5.59 per cent copper. Two other drillholes which intersected the fault at 45 and 61 m vertical depths found only weak mineralization. The mine workings have not been dewatered for several years but the crushing plant is occasionally used to treat small tonnages of cupreous ore from other workings in the area.

The Kumarina Open Cut line of workings extends over 600 m in a northwesterly direction (Fig. 32), at or close to a dolerite (west) and shale contact striking in the same direction. Subvertical veinlets of malachite, chrysocolla, cuprite, limonite and quartz occur in a zone up to 1 m wide. Feeble copper mineralization can be seen in all the pits and gougings, some of which are being worked in a minor way at present.

The Kumarina North show consists of a limonite-quartz-weak chrysocolla/malachite vein 40-100 cm thick, which is subvertical, northeast striking, and occurs at a shale (west) and dolerite contact. Shallow (4 m) workings follow the vein for 55 m.

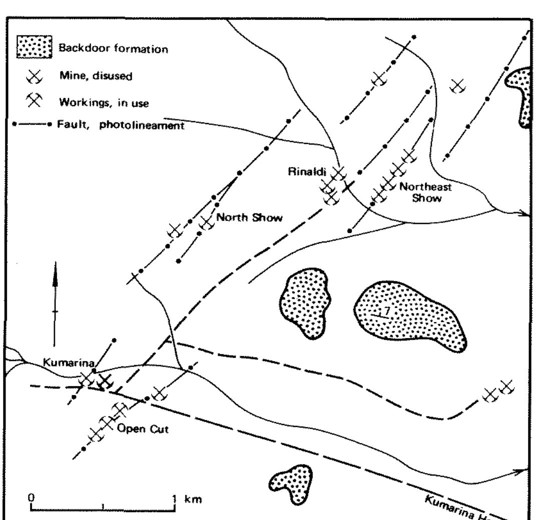


Figure 30. Copper workings in the Kumarina group

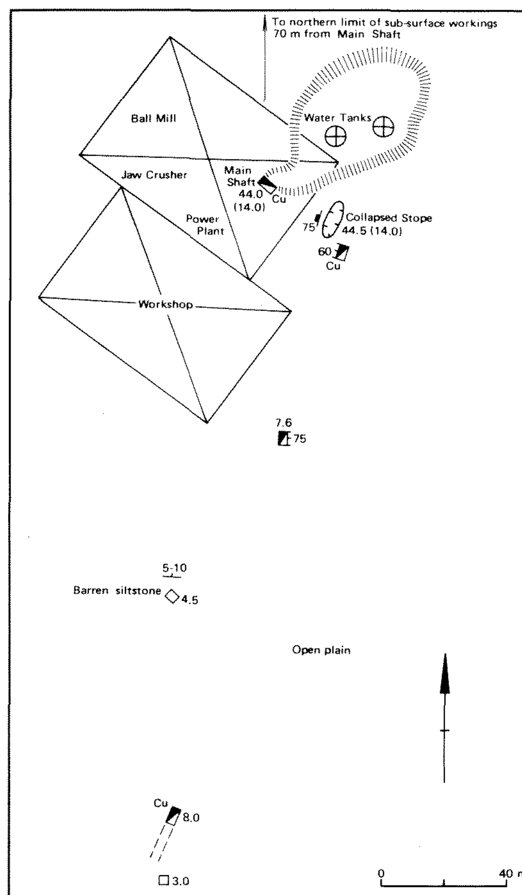


Figure 31. Surface plan of Kumarina copper mine

At Rinaldi mine (Fig. 33) a curvilinear, sporadically mineralized fault has been traced for 180 m and opened up in a cut 36 m long where a 2 m wide zone of clay, quartz, malachite, azurite and chalcanthite is exposed. A shaft was sunk to intersect this steeply west-dipping mineralized zone below the water table, and a level was driven at 15 m depth. Primary iron sulphides (pyrite and pyrrhotite) are present at a much shallower depth than at Kumarina mine, but chalcopyrite was not evident in material on the dump from the main shaft. That the country rocks are grey shale and siltstone with some dolerite is evident from the mullock excavated from the open cut.

The Kumarina Northeast show consists of a weakly mineralized faulted contact between shale (west) and dolerite, which has been traced in a northeasterly direction for 60 m. Four shallow openings (maximum depth 3.3 m) are scattered along the mineralized zone which is up to 1 m wide in a small costean.

BUTCHER BIRD MINE

This small copper mine (24°25′00″S, 119°43′10″E) is 15.8 km east-southeast of Ilgarari Outcamp and 1.6 km southeast of the Great Northern Highway. The mine occurs in a red-soil flat near the centre of a 4-km-long, northeast-striking photolineament. The lineament coincides with a steeply southeast-dipping fault in shale and siltstone of the Ilgarari Formation, which is only seen as dump material

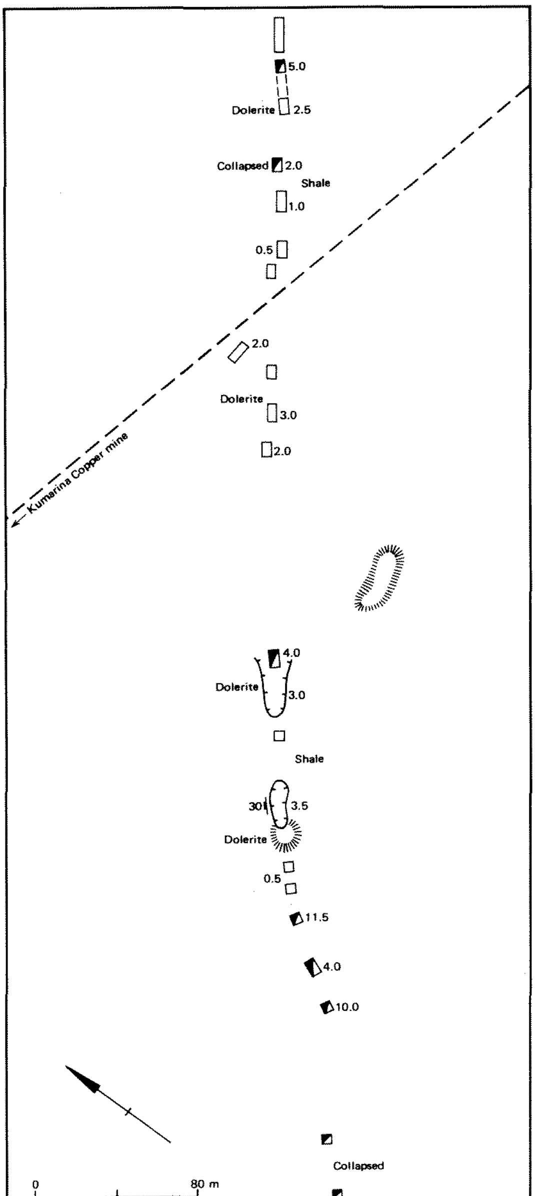


Figure 32. Surface plan of Kumarina Open Cut workings

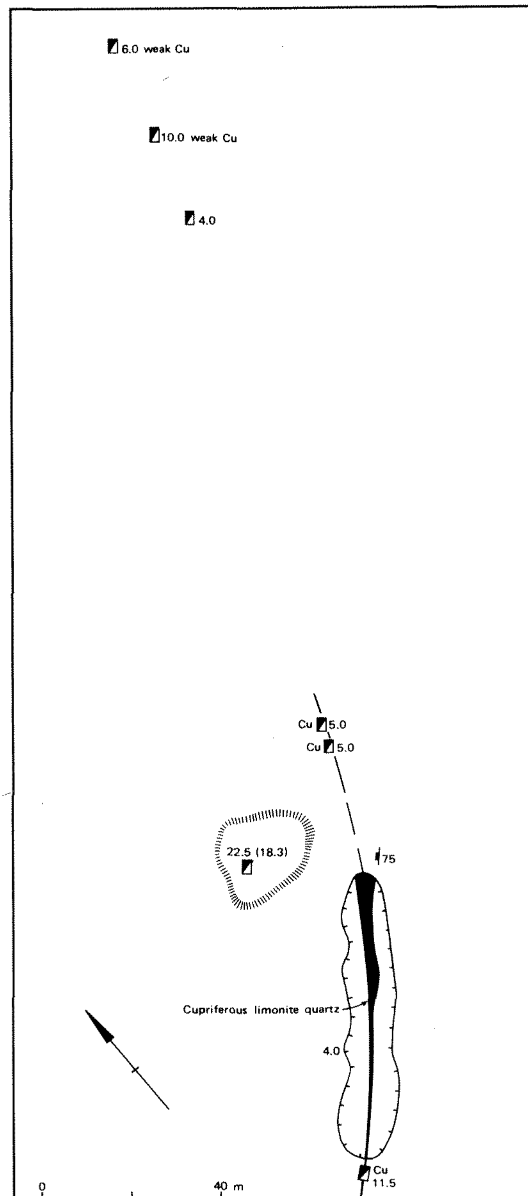


Figure 33. Surface plan of Rinaldi mine

at the mine. The fault has been opened up over 180 m, principally by an 11-m-deep shaft and two open cuts 2 to 4 m wide, 4 m deep and totalling 35 m in length. A crosscut from this drive gave access to a 14 m long drive at 9.1 m depth. Here disseminated and veiniform cuprite, malachite, azurite, chrysocolla and chalcocite occur in a 0.6 to 2.0 m wide mineralized zone in fault breccia, accompanied by vein quartz. Channel sampling of the mineralized zone has yielded average copper assays of about 5 per cent. A small tonnage of copper ore was produced in 1916-1918 (Table 28).

TOWERS FIND PROSPECT

This prospect (24°16′10″S, 119°28′30″E) is 14 km west-northwest of Ilgarari Outcamp and has also been known as Mountain Maid, Nounena, and Cawse. It is situated on the Neds Gap Fault trending 055 to 060 degrees, which forms part of the Tangadee Lineament and juxtaposes Kurabuka Formation (west) and Ilgarari Formation. Malachite, chrysocolla and limonite occur as stringers and disseminated in the fault zone which contains dolerite and green shales, or kaolinized versions of these rocks.

NEDS GAP PROSPECT

Neds Gap prospect (24°14′00″S, 119°33′00″E) is 9 km northeast of Towers Find, and also lies on the Neds Gap Fault. Chrysocolla, malachite and chalcocite occur over a 30 m strike length in vein quartz or kaolinized shale, and have been prospected by two vertical shafts and some costeans. Gypsum gangue is visible in one shaft. In 1967 Conwest reported that the prospect had previously produced about 50 t of 11 per cent copper ore, but there is no official record of this.

KOODE MAGI PROSPECT

At this locality (24°10′00″S, 119°34′40″E) 9.7 km west-southwest of Bloodwood Well, copper mineralization, similar in style to that of Neds Gap, occurs in a fault trending 055 degrees, which cuts pale weathering shale of the Fords Creek Shale. Chrysocolla, malachite, chalcocite, limonite and manganese oxide are accompanied by opaline silica, gypsum and quartz. There are several shallow shafts along the mineralized line and a small tonnage of cupreous ore was produced in 1962 (Table 28).

SCOTTY PROSPECT

Scotty prospect (24°02′30″S, 119°39′00″E) is 10 km east-southeast of Bulloo Downs homestead, near a creek crossing. Stringers and disseminations of chrysocolla and minor malachite occur in a shear trending 080 degrees developed in weathered medium-grained dolerite. Several shallow shafts and costeans trace out the mineralization. A production of 4.13 t of cupreous ore assaying 18.73 per cent copper recorded for 1970 from "Scotties Centre" (PA 943), is probably attributable to this prospect.

MULGUL PROSPECT

A small prospect (24°44′20″S, 118°18′00″E) occurs 20.5 km northwest of Mulgul homestead in rocks of the Devil Creek Formation. Thin-bedded dolomite, shale and chert dipping at 30 to 55 degrees to the southwest are intruded by a sill of medium-grained dolerite. Lenses of quartz-limonite-chrysocolla-malachite less than 1 m long and 10 to 20 cm thick are located near the basal contact of the dolerite. Cupriferous limonite veinlets also transverse the dolerite and sedimentary rock adjacent to these lenses. The mineralization is exposed in a small 2.5-m-deep pit and appears to be very limited in extent. A small tonnage of hand-picked cupreous ore was produced in 1956 (Table 28). Two percussion drillholes, collared 25 and 50 m to the southwest, were sited to test for down dip extensions but were apparently unsuccessful.

MORAWA WELL PROSPECT

A small prospect (24°00′10″S, 119°11′40″E) 1 km southwest of Morawa Well consists of malachite and chrysocolla disseminations in a 20-cm-wide, vertical shear zone trending 030 degrees, which cuts a dolerite intrusion. Quartz veinlets are also present in the shear. A 3 m-deep shaft and some pits have been excavated recently along the mineralized zone.

STRATIFORM ZINC-COPPER OCCURRENCES (TYPE B)

The black pyritic shale—stromatolitic dolomite—chert lithological association of the western facies of the Bangemall Group has elements in common with environments associated with both sedimentary copper deposits of the Copperbelt-type (Jacobsen, 1975, p. 350-355, Mendelsohn, 1976), and sedimentary zinc-lead-copper deposits of the McArthur River or Rammelsberg type. Carbonaceous pyritic shales of the Discovery Chert, Jillawarra Formation and Kiangi Creek Formation have been found to be regionally anomalous in zinc, copper and lead, from the results of extensive stream sediment and soil geochemical surveys conducted by exploration companies. Surface coatings of chrysocolla, malachite, and complex hydrous zinc salts (e.g. goslarite) accompanied by limonite gossans after pyrite, are the visible, outcrop expressions of this mineralization at isolated occurrences such as Mount Palgrave (23°24′30″S, 115°55′00″E; and 23°21′50″S, 115°57′30″E), Glen Ross (24°18′30″S, 118°12′50″E; 24°18′30″S, 118°10′00″E; 24°18′30″S, 118°09′20″E), High Range (23°40′40″S, 115°38′20″E), and Brumby Creek (24°16′40″S, 118°43′00″E).

Although surface material may assay up to several per cent copper, lead or zinc, deep drilling commonly reveals values only of up to 1 000 ppm zinc, 300 ppm copper and 150 ppm lead. The best results of percussion and diamond drilling in the Mount Palgrave area by Westfield in the mid 1960's (Blockley, 1971b, p. 195) were 0.67 per cent copper between 29.26 and 31.09 m (PDH 30) at prospect 3A (23°24′30″S, 115°55′00″E), and 3 per cent copper between 18.29 and 24.38 m (PDH 19) at prospect 2 (23°21′50″S, 115°57′30″E). The Glen Ross Shale Member of the Kiangi Creek Formation in the Mount Vernon area was also investigated by Westfield at that time, but the highest copper assay from three diamond drillholes was 1 000 ppm over 11 m (DDH 2) which also averaged 1.2 per cent zinc (Blockley 1971b, p. 195). Marshall (1968) notes that the main primary sulphides are pyrite, sphalerite and covellite in Bangemall Group shales in general (see Appendix 1). High copper-zinc values correlate with high pyrite content, low quartz to clay ratios and possibly with the presence of diagenetic carbonate.

LEAD-COPPER MINERALIZATION (TYPE C)

Several minor occurrences of lead-copper mineralization, most of them in small quartz veins within the Irregully Formation, have been reported by Blockley (1971b). At McCarthy Find (24°05′S, 116°45′E), Mount Isabella (23°21′S, 116°40′E) and Latham prospects (23°31′S, 115°40″E) malachite and chrysocolla accompany galena in quartz veins. At Joy Helen prospect (23°15′00″S, 115°46′20″E) galena, and minor sphalerite, malachite, azurite and chrysocolla occur in irregular segregations that may be parallel to the bedding of a silicified (?) algal breccia dolomite of the Irregully Formation.

OTHER OCCURRENCES

The Boondawari Creek occurrence (23°31′00″S, 121°30′30″E) is the only one known from the eastern part of the basin (east of 120°E). Boulders of dolerite contain specks of malachite, atacamite and limonite. The dolerite presumably intrudes gently dipping rocks of the McFadden Sandstone which crop out nearby.

A copper occurrence (22°31′10″S, 115°40′50″E) 2 km south of Warrada Creek Well is shown on the Wyloo Sheet (Daniels, 1970) in dolomite of the Irregully Formation, close to a north-trending fault.

CHAPTER 13

Nabberu Basin

GEOLOGY

The Lower Proterozoic sedimentary and subordinate volcanic rocks of the Nabberu Basin (Hall and Goode, 1975) crop out over an area of some 65 000 km^2. The basin is geographically and stratigraphically between the Middle Proterozoic Bangemall Basin to the north and the Archaean Yilgarn Block to the south. Phanerozoic rocks of the Officer Basin unconformably overlie the basin to the east. The western boundary (on Robinson Range Sheet) is a tectonized unconformity with Archaean rocks of the Yilgarn Block and gneisses of the Gascoyne Province. Structurally the Nabberu Basin is an arcuate synclinorium with:

(i) a tilted or gently folded and essentially unmetamorphosed southern portion termed the Kingston Platform, and

(ii) a moderately to tightly folded, cleaved and metamorphosed northern portion termed the Stanley Fold Belt (Bunting and others, 1977).

This change in tectono-metamorphic style is probably related to a change from a stable Archaean basement in the south, to a crystalline basement reworked by post-Archaean events (possibly event 3, Table 25) in the north (Bunting and others 1977).

TABLE 29. STRATIGRAPHY AND CUPRIFEROUS MINERALIZATION OF THE NABBERU BASIN

	Formation	Mineralization and remarks
	Earaheedy Sub-basin	
Earaheedy Group	Mulgarra Sandstone	
	Kulele Creek Limestone	Stromatolitic in part
	Wongawol Formation	Fine sandstone and siltstone
	Princess Ranges Quartzite	
	Wandiwarra Formation	Fine micaceous sandstone
	Windidda Formation	Carbonates and fine clastics
	Frere Formation	Pelletal ferruginous chert
	Yelma Formation	Quartz sandstone
	slate, phyllite, sandstone and chert	Equivalent to "Axial Sequence"(?)
	Glengarry Sub-basin	
Padbury Group	Millidie Creek Formation	Hematitic shale, wacke, chert carbonate, BIF
	Robinson Range Formation	Hematitic phyllite
	Labouchere Formation	Quartz sandstone, phyllite, metabasalt
"Axial Sequence"	Horseshoe Beds	BIF and hematitic Mn shale
	Metagreywacke, purple slate, arkose, quartz-muscovite schist, chert metabasalt, felsic metavolcanic rocks	Copper-bearing limonitic quartz veins and shears, disseminated copper in quartz-mica schist
	Maraloou Formation	Carbonates and fine clastics
	Finlayson Sandstone	Quartz sandstone

Bunting and others (1977) have subdivided the Nabberu Basin lithologically into the western, Glengarry Sub-basin and the probably younger, eastern, Earaheedy Sub-basin (Table 29). The Earaheedy Sub-basin contains a 6 km thick, shelf facies sequence of shale, sandstone, limestone and pelletal iron-formation called the Earaheedy Group (Hall and others, 1977). The stratigraphy of the Glengarry Sub-basin is complicated by facies changes, and is not yet fully understood. A 2-km-thick shelf-type sequence of quartz-arenite, shale, siltstone and carbonate (Finlayson Sandstone and Maraloou Formation) occurs in the southeast on the Kingston Platform, and is replaced northwestwards by a deeper water, mixed sequence of metamorphosed arkose, greywacke and mudstone, and minor basalt and felsic volcanic rock, collectively called the "Axial Sequence" by Bunting and others (1977). In the Thaduna area, the local term "Thaduna Beds" was previously applied to these rocks (MacLeod, 1970). In the northwestern part of the sub-basin a 10-km-thick sequence of metamorphosed shallow-water arenites, iron-rich shale and banded iron-formation, collectively termed the Padbury Group (Barnett, 1975), overlies ?disconformably the Axial Sequence (Bunting and others, 1977). The lithological similarity between the Padbury Group and parts of the Earaheedy Group was pointed out by Hall and Goode (1975) and Bunting and others (1977). Present evidence suggests that the Nabberu and Hamersley Basin sequences are not equivalent in age, despite the presence of extensive iron formations in each.

MINERALIZATION (MAINLY TYPE C)

Known cupriferous mineralization of importance is restricted to the "Axial Sequence" of the Glengarry Sub-basin. This mineralization is found in metagreywacke and slate at the Thaduna mine group, and in quartz feldspar-muscovite-chlorite schist and felsic metavolcanic rocks in the Horseshoe Lights mine group. In terms of contained copper, the mines of the Thaduna group (Thaduna, Rooney, Ricci and Green Dragon, see Fig. 34) have produced 98 per cent of the total copper won from the Nabberu Basin to date (Table 30). Copper mining took place from 1942 to 1971, a period which coincides with the local market for cupreous ore. The mineralization is oxidized and moderately enriched to depths of 50 to 200 m and was therefore well suited to the type of demand then current.

In the Thaduna area (Fig. 34), mineralization is confined to north-northwesterly and easterly trending faults which are characterized by graphitic and quartz gangue in addition to brecciated country rock. The mineralized sections of the faults are up to 3 m wide and 600 m long. Primary sulphide mineralization averages less than 1 per cent copper and is disseminated or in veinlets with varying amounts of carbonaceous material and hydrothermal quartz. Oxidized and supergene sulphide mineralization ranges in grade from 3 to 12 per cent copper. Small tonnages of low-grade (2 per cent or less copper) remain in the dumps at Thaduna, and some medium-grade ore remains underground. Neither would be economic to exploit with conventional treatment methods at present.

The style of mineralization is different at Horseshoe Lights mine which began life as a gold mine and has provided far more revenue from gold than copper. The country rocks however are similar to, though more deformed and metamorphosed than those at Thaduna. A felsic volcanic element is evident in the host rocks of both areas, although the lack of zinc mineralization suggests that this is incidental insofar as ore genesis is concerned. Pyrite and minor chalcopyrite occur in a broad stratabound zone as disseminations and veinlets, and in areally more restricted, thin massive horizons.

Oxidation has taken place to in excess of 200 m depth, and has enriched the primary mineralization to workable values. Patches of medium-grade ore have also been extracted from cross-cutting limonite-quartz veins in the area. The indications are that mineralization at Horseshoe Lights is not of economic interest, although poorly exposed felsic volcanic rocks in the area may be worth prospecting.

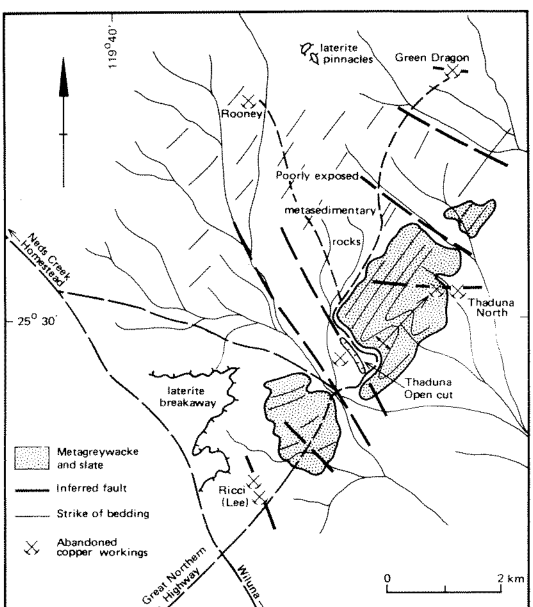


Figure 34. Copper workings in the Thaduna group

TABLE 30. MINE PRODUCTION OF COPPER FROM THE NABBERU BASIN

Mine	Copper ore and concentrates (t)	Cupreous ore and concentrates (t)	Average grade (%)	Contained copper (t)
Cashman	6.83		16.55	1.13
Green Dragon		(ca 200 t 8% Cu, probably included with Thaduna)		
Horseshoe Lights		553.50	8.72	48.03
Ricci (Lee)	128.28		13.28	17.04
		2 783.35	9.55	269.93
Rooney	16.26		24.97	4.06
		103.39	7.67	7.93
Thaduna	267.77		11.52	30.85
		30 527.82	8.18	2 497.38
PA 761	12.40		12.10	1.50
Totals	431.54	33 968.12	[1]8.34	2 877.86

[1]. Overall weighted average for copper and cupreous ore and concentrates combined.

THADUNA COPPER MINE

Thaduna (Nabberu) copper mine (25°30'30"S, 119°42'30"E) is some 56 km east of the Great Northern Highway in gently undulating terrain containing low ranges of northeast-striking, green metagreywacke and purple slate of the "Axial Sequence" (Fig. 34). The bedding dips at moderate to steep angles. It is accompanied by a steeply northwest-dipping, fanning, slaty cleavage, which is axial planar to gently northwest-plunging asymmetric folds that vary from open to moderately appressed in style. Trendall (1970) has described the host rocks as resorted tuffs. The detailed solid geology of the mine area shown in Figure 35 is modified after Blockley (1968b), who gives a detailed account of the mine geology and the history of mining and drilling up to that date. This is summarized and updated here.

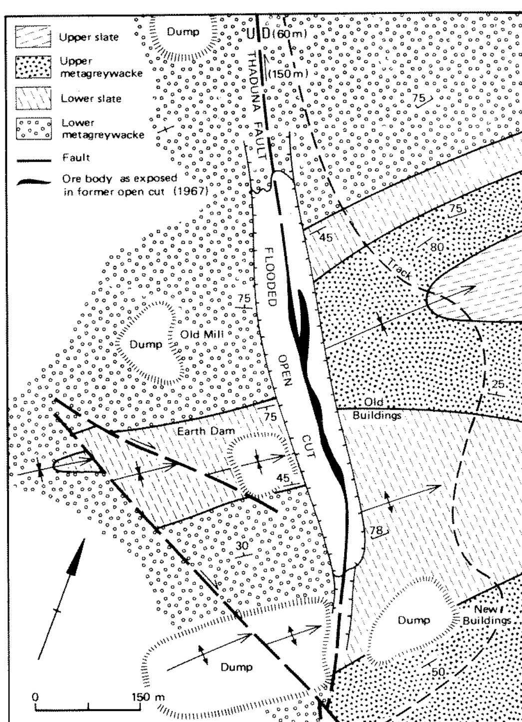


Figure 35. Surface plan of Thaduna copper mine with solid geology shown

Copper mineralization is confined by the Thaduna fault which trends 340 degrees, and is a subvertical sinistral fault that also downthrows to the east. The mineralized part of the fault is 600 m long and an average of 3 m wide, though in places veinlets and disseminations in the wall rocks may increase this width to a maximum of 21 m. The lithological nature of the gangue varies from (a) graphitic schist and breccia containing country rock fragments, to (b) quartz-cemented breccia, and (c) silicified shear with quartz veinlets and country rock inclusions, to (d) white reef quartz. Calcite and ankerite are present in the gangue locally. The vertical zonation of ore minerals is as follows:

Zone	Ore minerals	Depth	Average tenor Cu
Near surface	Chrysocolla	Surface to 3-6 m	4%
Oxidized	Malachite, azurite and cuprite	Surface to 15-46 m	4%
Supergene	Chalcocite (plus covellite and neodigenite)	15-46 m to 19-120 m	3.5%
Primary	Chalcopyrite and bornite	Below 90-120 m	1%

Minor amounts of pyrite occur in the primary zone. No mining has taken place in the primary zone. The better ore in the oxidized zone averages 6 to 8 per cent copper, and in the supergene zone 8 to 10 per cent copper. The better grade ore occurs where the fault is carbonaceous and poor in hydrothermal quartz, and hence more permeable. Blockley (1968b) reported hydrothermal alteration of wall rock within 15 m of the mineralized zone, expressed by the introduction of chlorite, calcite and graphite.

The siting of the mineralization in a restricted part of the Thaduna fault is ascribed by Blockley (1968b) to the development, during fault movements, of openings and branching shears where the fault trace curves (Fig. 35). The most favourable sites for supergene enrichment appear to have been at each end of the curved trace, where the fault was most carbonaceous and not "sealed" by the cementing of rock fragments by hydrothermal quartz in the wider fault openings in the centre.

Mining began in 1942 and continued on a small scale until 1953. In 1952, two diamond drillholes and costeans were put into the deposit by Anglo-Westralian, but interesting results were not obtained. In 1955, Thaduna Copper Mines N.L. (latterly owned by BMC) was formed to work the property by open cut methods for cupreous ore, and production continued until 1971, except for a break in 1967-1968. During this time the mine was one of the State's major producers of cupreous ore, total production of ore and concentrates amounting to 30 528 t averaging 8.18 per cent copper. Deep mining to a depth of 50 m took place in 1960-1962 in the northern part of the mineralized zone.

In 1962 Gold Fields obtained an option on the mine and bored eight diamond drillholes into the mineralized zone but failed to find important reserves of secondary ore, or any encouragement from the low grade of primary sulphides intersected. However medium-grade chalcocite ore was intersected at 105 to 122 m vertical depth, and BMC drilled a further ten diamond drillholes (960 m total length) in 1966-1967 in an attempt to determine the reserves of deeper secondary ore in the southern part of the zone. Blockley (1967) estimated indicated reserves at 14 000 t averaging 6.5 per cent copper (at 2 per cent cut off) plus 6 700 t averaging 5.8 per cent copper. A further three drillholes designed to test the north and south extensions of mineralization along the fault added nothing to these reserves. Blockley (1968a) estimated indicated reserves of 183 000 t averaging 3.7 per cent copper, based upon results of all previous drilling and channel samples from the floor of the open cuts. In terms of the geometry of the orebodies, Blockley (1968b) interpreted these results as indicating a series of north-pitching shoots 45 to 61 m long, ranging in grade from 6.5 per cent to 10 per cent copper.

A further three drillholes (DDH 28, 29 and 30) totalling 199 m were bored by BMC in 1968 to refine reserve calculations to the 61 m level. In 1970, a much enlarged open cut (Fig. 35) was excavated. Ore totalling 50 800 t was stockpiled, and 1 067 t of cupreous concentrates averaging 15 per cent copper were produced in a new grinding mill and flotation plant. At the same time an open cut was put in at the Green Dragon mine, but both open cuts were made excessively wide and caused unnecessary dilution of some ore. The treatment plant was unable to cope efficiently with the mixed sulphide-carbonate-silicate copper minerals and operations ceased in December, 1970.

In an attempt to locate ore shoots along projected extensions of the Thaduna fault to the north-northwest, 1 899 m of auger drilling along a 17 km long line was carried out in 1970-1971 by BMC. In addition, 898 m of auger drilling was done along a 7.2 km line on a projected east-west fault between Green Dragon and Rooney. Only three copper-anomalous samples were found on each line.

RICCI COPPER MINE

The Ricci (Lee) copper mine (25°31′40″S, 119°41′40″E) is 3 km south-southwest of Thaduna mine in a thinly timbered flat (Fig. 34). The mine was worked from 1942 to 1970 for a production of 2 911.63 t of ores and concentrates containing 286.97 t of copper. The bulk of production was cupreous ore, which was concentrated in the later years at a small crushing and flotation plant set up adjacent to a laterite breakaway 1 km west-northwest of the mine. The workings occur in three *en echelon* groups oriented at 350 degrees and extending over 400 m, and are deepest in the south (Fig 36).

The country rocks are weathered metagreywacke and slate striking east-northeast to northeast, and visible only in the workings. The principal mineralized shears strike 350 degrees but there are subordinate directions (Fig. 36). A 1 to 3-m-wide zone of graphitic breccia cemented by limonite and quartz, contains veinlets, pods and disseminations of malachite, azurite, cuprite and chalcocite, Visible mineralization is discontinuous and weak, and the ore shoots appear to have been small, though medium grade, and west-plunging.

THADUNA NORTH PROSPECT

A line of quartz lenses and stringers oriented 280 degrees occurs 2 km northeast of Thaduna. The quartz contains patches of limonite, and weak malachite staining and veinlets, which may also occur in the immediate wall rocks. A shallow, collapsed shaft and a group of small excavations 450 m to the east have tested the apparently weak and unimportant mineralization filling a fracture. There is no recorded ore production.

ROONEY MINE

This small mine (25°28′00″S, 119°41′40″E) is 5 km north-northwest of Thaduna, and has produced a small tonnage of cupreous and copper ore (Table 30). All that is visible of the old workings is a 20 m deep shaft and a 3 m deep pit adjacent. Bulldozed costeans have been excavated in an attempt to trace the mineralization. A subvertical shear zone striking about 090 degrees contains weak malachite disseminations and veinlets over a maximum width of 1 m and is traceable for about 200 m. The host metasedimentary rocks are folded and cleaved, and strike at 035 degrees. Carbonaceous material occurs in mineralized rocks.

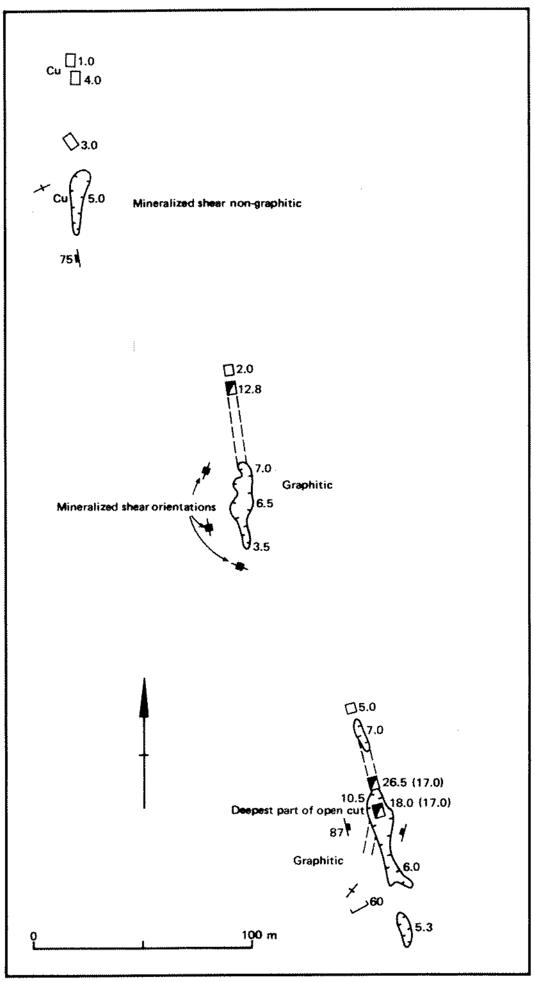
GREEN DRAGON MINE

Green Dragon mine (25°27′50″S, 119°43′50″E) is 5 km north-northeast of Thaduna. The country rocks are poorly exposed and weathered, but are similar to those at Thaduna. The old workings consisted of 6.1-m-deep and 30.5-m-deep shafts, and a stope from the eastern side of the deepest shaft from which about 200 t of 8 per cent cupreous ore was extracted. Two graphitic shears trending 090 degrees and 060 degrees, which cropped out through a laterite capping, carried at their intersection, cuprite-chalcocite-malachite mineralization in the form of a 50 m long shoot oriented east-west. In 1967-1968 a partly government subsidized diamond drilling programme (eleven drillholes totalling 892 m) was carried out by BMC and the Mines Department (Blockley, 1968a). This drilling defined three sub-parallel and closely spaced (50 m) mineralized shears oriented east-west, including the southernmost one previously mined. The mineralized intersections were 0.5 to 5.2 m wide and assayed between 0.35 and 12 per cent copper the best intersection being 3.7 m of 11 per cent copper in a chalcocite-rich graphitic shear. Supergene mineralization is found to a vertical depth of 53 m. Based on a 46 m strike length, Blockley estimated indicated reserves of 45 000 t at 6 per cent copper to a depth of 46 m.

Subsequently, in 1970, an open cut 300 m long (east-west), up to 45 m wide and 20 m deep was excavated and ore was carted to Thaduna for treatment. The remaining mineralization in shears (the southernmost ore zone) on the south wall is weak and unimpressive.

HORSESHOE LIGHTS GOLD-COPPER MINE AND AREA

Horseshoe Lights mine (25°21′20″S, 118°37′10″E) is 8.5 km at 045 degrees from Mount Beasley, a summit which lies 3 km north of the Horseshoe manganese deposit. The country rocks are folded, cleaved or schistose metasedimentary rocks including pebbly quartz metagreywacke, lithic meta-arkose, graded-bedded metasiltstone and fine sandstone, and in the vicinity of the mine, quartz-feldspar-muscovite-chlorite schist and phyllite, quartz-eye sericite and quartz schist, and limonitic quartz-mica schist with thin psammitic beds. The strike of bedding is variable because of folding, but in the mine area is north-northwesterly with a steep westerly dip, and is accompanied



GSWA 17295

Figure 36. Surface plan of Ricci (Lee) copper mine

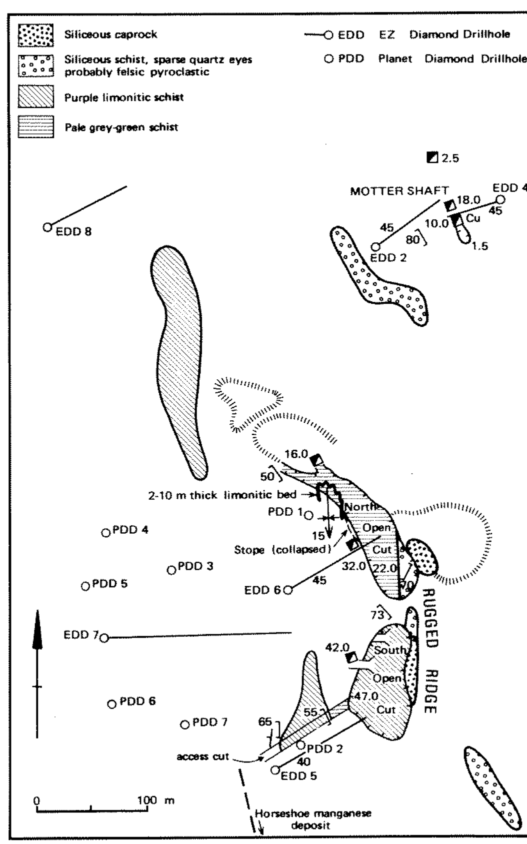


Figure 37. Surface plan of Horseshoe Lights gold-copper mine

by a sub-parallel cleavage or schistosity (Fig. 37). There is no visible copper mineralization except at Motter shaft. In the north and south open cuts deeply weathered purple limonitic (formerly pyritic) schist predominates and locally contains deformed and post-tectonic barren quartz veins up to 40 cm thick, which may form weak stockworks. In the western wall of the northern open cut a folded massive limonitic "bed" appears to have been stoped along the eastern limb of a gently south-plunging synform. Presumably this bed assays copper.

In 1964-1967, EZ bored 1 275 m of inclined diamond drillholes (eight) into the property, principally targeted on induced polarization anomalies. Disseminated pyrite was found in carbonaceous slate, "silty tuffs" and quartz-dolerite intrusives. Minor chalcopyrite was found in the slate but more particularly as fine grains and veinlets in green, kaolinized schist. Only one drillhole cut fresh rock below about 210 m vertical depth. In 1969, Planet carried out 1 625 m of vertical diamond drilling (seven holes) west of the open cuts, the best intersection being 39 m drilled width assaying 0.6 per cent copper in oxidized rock (PDD3). Two 9.1 m lengths in the same hole, from 180 to 305 m depths assayed a little over 1 per cent copper. The better mineralized portions were narrow and lenticular in dip and strike, and there seems to have been little enrichment of the largely, weakly disseminated, copper-poor sulphide mineralization. A further three diamond drillholes (873 m) put in by Amax in 1976 did not find any encouragment.

The mine was opened as a gold mine in 1946 and began producing token amounts of cupreous ore in 1950 with intermittent production until 1966. Most of the ore seems to have come from the Motter workings and the stope in the north open cut.

The Motter B show (25°22′20″S, 118°39′30″E) is 4 km east-southeast of Horseshoe Lights in poorly exposed terrain underlain by north-northwest-striking quartz-mica-chlorite schist, ferruginous quartzite, psammitic schist and quartz-eye sericite schist (foliated felsic metavolcanic rock). Shallow pits have been dug in fuchsitic siliceous schist. Copper-anomalous gossanous material has been found in the general area.

Low (1963, p. 116) mentions a small copper prospect (PA 761) about 13 km east of Horseshoe (manganese deposit), which produced 12.40 t of copper ore in 1942. The prospect has not been inspected.

Barnett (1975, p. 54) mentions the occurrence of malachite and bornite in a quartz vein emplaced in dolomite of the Labouchere Formation, 9.5 km west-northwest of Mount Labouchere, and 1 km north of the Milgun-Yarlarweelor road. The vein has been opened up in a costean.

WONYULGUNNA PROSPECTS

The next ridge south of Wonyulgunna Hill lies 16 km southwest of Kumarina Hotel. It comprises strongly and complexly deformed quartz-feldspar-chlorite and quartz-feldspar-muscovite schist striking 075 to 085 degrees and dipping steeply north. Laminae and pods of deformed vein quartz occur in the main schistosity, which contains a down dip mineral lineation, and a subhorizontal crenulation lineation plus later kink folds. These rocks may represent an inlier of "Axial Sequence" on the northern margin of a large area of granitoid and gneiss called the Marymia Dome (Bunting and others, 1977), which occurs east of Horseshoe Lights and north of Thaduna. Though much fresher in outcrop, the country rocks and the patchy disseminated mineralization are similar to those at Horseshoe Lights. On the other hand, this could be a belt of Archaean rocks, as there are similarities with the Jimblebar area in the Sylvania Dome. The mineralized areas are scattered through the ridge and are:

(i) purple-weathering zones a few metres long and less than 50 cm wide, and

(ii) small, cupriferous, limonitic vein quartz pods in the schistosity.

The visible mineralization is weak and of very limited extent. Percussion drilling by Endeavour in 1971-1972 indicated average copper assays of less than 0.5 per cent in the oxidized zone (malachite, azurite, cuprite) with values decreasing into the sulphide zone (pyrite and chalcopyrite).

CASHMAN COPPER MINE

Cashman (Cashburn, Holden Find) mine (25°58′00″S, 118°37′10″E) produced a few tonnes of copper ore in 1917 (Table 30), and is situated 250 m due east of the old gold workings (Hard to Find) and at the eastern end of a low, rough outcrop of meta-basaltic tuff and breccia. These rocks are near the southwestern margin of the Nabberu Basin, and appear to dip gently northwards. An irregular, subvertical, massive cupriferous limonite vein strikes 042 degrees, dips steeply to the northwest and is up to 1 m wide. Disseminations and veinlets of chrysocolla and malachite occur in the vein and the immediate wall rocks. The visible length of the vein, as exposed in an 11 m deep shaft and an adjacent gouging, is only 4 m.

JILLAWARRA ZINC-LEAD-COPPER PROSPECTS

Near Quartzite Well (24°38′40″S, 118°20′00″E), several thin zones of low-grade chalcopyrite-bearing mineralization have been recently discovered by Amoco in sheared chloritic rocks. These rocks occur in an east-west oriented, elongate basement inlier in the central Bangemall Basin, and they may be correlatable with rocks of the Glengarry Sub-basin.

CHAPTER 14

Eastern border region crystalline terrains

Included in this category are (from north to south) the Granites-Tanami Block, the Arunta Block, the Petermann Ranges Nappe and the Musgrave Block (excluding the cover rocks of the Bentley Supergroup). The bulk of each of these provinces lies outside the State, in the Northern Territory or South Australia.

The geology and mineralization of the Granites-Tanami Block has been summarized by Blake and Hodgson (1975). Folded and mildly metamorphosed clastic, sedimentary and mafic to felsic volcanic rocks of the "Tanami Complex" are intruded by post-tectonic granitoids. The Tanami complex is Lower Proteroic in age and is correlated with the Halls Creek Group of the Halls Creek Province by Blake and Hodgson (1975). Extensive stratiform gossans have been reported from the Tanami complex, but they appear to relate to pyritic black shale-slate. Chalcopyrite has been noted from chloritic phyllite adjacent to pyritic black slate (Blake and Hodgson, 1975).

The Arunta Block in Western Australia consists of Lower Proterozoic, low-grade to medium-grade metasedimentary and minor metavolcanic rocks intruded by granitoid rocks. There is no mineralization recorded from these rocks, but similar rocks in the Northern Territory contain small pegmatitic or metasomatic tungsten-molybdenum-tin-copper, and stratabound copper-lead-zinc deposits, both emplaced in fractures (Stewart and Warren, 1977).

The Petermann Ranges Nappe comprises Lower Proterozoic igneous and metamorphic rocks, and unconformably overlying metasedimentary and metavolcanic rocks, which are probably continuous in subcrop with the Musgrave Block to the south.

The area is poorly known and there are differences in regional geological interpretations (Trendall and Cope, 1975). There are no recorded occurrences of copper mineralization in the area.

The western third of the Musgrave Block extends into Western Australia, and this portion has been described by Daniels (1974). For the purposes of this bulletin the Middle Proterozoic sedimentary and volcanic rocks of the the Bentley Supergroup are excluded from the Musgrave Block and described in a separate chapter. Granulites, migmatites, gneisses and granitoid rocks make up the bulk of the block, but no copper mineralization has been reported from them. The layered gabbroidal rocks of the Giles Complex intrude these rocks (and the Bentley Supergroup) and contain traces of copper at the following localities (Daniels, 1974 p. 234):

(1) minor disseminated chalcopyrite with ilmenite, magnetite, pyrite and a trace of pyrrhotite and ?pentlandite in gabbro of the Michael Hills Gabbro between Michael Hills and Sphinx Hill (ca. 26°15′S, 128°55′E);

(2) minor chalcopyrite and chalcocite in a small, dyke-like body of gabbro 7.2 km south of Mount Gosse (ca. 25°55′S, 128°57′E);

(3) two titaniferous magnetite bands in the Jameson Range Gabbro southwest of Jameson Range (ca. 25°48′S, 127°36′E) carry copper stains on joint faces; the magnetite contains minute inclusions of chalcopyrite and covellite;

(4) a xenolith of quartzite and tuffaceous rock within Jameson Range Gabbro at Domeyer Hill (25°39′30″S, 127°28′00″E) contains copper staining.

The prospect of finding mineralization of sufficient magnitude to be economic in any of these remote regions appears slight.

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CHAPTER 15

The Blackstone region: Bentley Supergroup

GEOLOGY

The Bentley Supergroup (Daniels, 1974) includes all sedimentary and volcanic rocks in the Blackstone region (Musgrave Block area) younger than the metamorphic and granitoid rocks of the Musgrave Block, but older than Upper Proterozoic glacigene rocks. The supergroup is probably Middle Proterozoic in age and an Rb-Sr isochron of 1 060 ∓ 140 m.y. was obtained by Compston and Arriens (1968) from acid volcanic rocks of the Tollu Volcanics. An age equivalence with the Bangemall Basin is indicated. The stratigraphy and mineralization of the supergroup is summarized in Table 31. The sequence is a continental volcanic one in which flow-banded rhyolites and ignimbrites are a conspicuous feature. The cauldron subsidence volcanic associations contain cogenetic hypabyssal granitoid rocks, and are up to 4 400 km² in outcrop area.

MINERALIZATION (TYPES B AND C)

CAULDRON SUBSIDENCE VOLCANIC ASSOCIATIONS

Daniels (1974, p. 233) mentions two locations in the Palgrave volcanic association which exhibit minor zinc-lead-copper mineralization. At an occurrence 6.4 km north-northeast of Mount Eliza (26°05′00″S, 127°26′50″E) a brown-weathering, dark, glassy rhyolite, contains pyrite, galena and chalcopyrite disseminations and assays up to 650 ppm copper, 1.15 per cent zinc and 0.41 per cent lead in surface grab-samples. One kilometre south of Mount Palgrave (26°03′10″S, 127°17′00″E) similar mineralization is seen in a probable volcanic plug of dark-grey granophyre, which may be a feeder for agglomerate and pyritic rhyolites in the vicinity. Copper occurrences are also located 7 km west-southwest and 10 km northeast of Mount Eliza, and 7 km northwest of Mount Palgrave.

Pyritic and bleached rhyolite containing traces of chalcopyrite is present along the southern faulted boundary of the Scamp volcanic association on the Talbot Sheet. Fluorite lenses and veins up to 41.0 m long and 10.6 m wide occur in brecciated felsic volcanics of the Scamp association 3.2 km west-northwest of Mount Elvire (26°04′50″S, 127°07′00″E). Minor amounts of copper and zinc minerals are present in these veins. A copper occurrence in the same association is located 4.2 km north-northwest of Scamp Hill (25°54′50″S, 126°42′50″E) on the Bentley Sheet.

Granophyre of the Skirmish Hill association is cut by a weakly cupriferous quartz vein 4.2 km northeast of Skirmish Hill (26°20′20″S, 128°28′30″E).

Daniels (1974, p. 233) recommended that all the cauldron structures be explored for copper and associated mineralization.

TOLLU AND PUSSY CAT GROUPS

Quartz veins in the Smoke Hill Acid Volcanics (Tollu Group) contain small amounts of chalcopyrite, covellite, chalcocite, cuprite, malachite and chrysocolla, at Tollu (26°09′00″S, 128°22′30″E), 13 km east of Smoke Hill.

At Pussy Cat Hill (26°03′40″S, 126°41′50″E) copper stains are present in sedimentary rocks and basic volcanics of the Glyde Formation.

MILESIA FORMATION

The Milesia Formation is at the top of the Mission Group and consists mainly of basalt with subordinate quartzite lenses, shale, and conglomerate. The formation is some 3 000 m thick, and crops out along the south-western margin of the Musgrave Block in the northern part of the Talbot Sheet.

Some 200 minor occurrences of copper have been reported from the formation mainly from the outcrops extending 20 km to the southeast of Warburton Mission, between the Warburton and Brown Ranges. During the tenure of TR's and a prospecting concession

TABLE 31. STRATIGRAPHY AND CUPRIFEROUS MINERALIZATION OF THE BENTLEY SUPERGROUP

Group	Formation	Mineralization and remarks
	Townsend Quartzite	
	?Unconformity	
Mission Group	Milesia Formation	1. Small hematite-chalcocite veins in basalt 2. Disseminated copper in matrix to conglomerate 3. Disseminated copper in amygdales in basalt 4. Rare chalcocite in quartzite 5. Minor copper in one shale
	Lilian Formation Frank Scott Formation Gamminah Conglomerate	Stromatolitic dolomite
Cassidy Group	Miller Basalt Hilda Rhyolite Warubuyu Basalt Thomas Rhyolite Gurgadi Basalt Gombugurra Rhyolite Wururu Rhyolite	
Skirmish Hill, Palgrave and Scamp volcanic (cauldron subsidence) associations: felsic and subordinate mafic volcanic rocks.		Minor Zn-Pb-Cu (+F) disseminations in felsic volcanic rocks
Tollu Group	Hogarth Formation Smoke Hill Acid Volcanics Mummawarrawarra Basalts MacDougall Formation	Cupriferous quartz veins
Pussy Cat Group	Glyde Formation Kathleen Ignimbrite	Tollu Group is probably the equivalent of this group in the west

covering an area of some 3 800 km² from 1966 to 1970, WMC inspected 132 of these occurrences and found 57 to be on cross fractures and 58 to be stratigraphically controlled. Costeans were excavated at 54 localities. Extensive geochemical surveys including 1 355 m of auger and vacuum drilling, confirmed that the Milesia Formation had a higher background copper content than other formations in the area.

Daniels (1974, p. 231-233) has summarized five main types of copper occurrences in this area as follows:

(1) chalcocite and subordinate malachite, atacamite, chrysocolla, azurite and covellite are present in hematitic veins up to 61 cm thick, 9 m long and 21 m deep, which occupy cross fractures in basalt and sedimentary rock;

(2) various copper minerals occur as disseminations in the matrix or as cross-cutting veinlets in conglomerate beds within basalt;

(3) chalcocite and bornite are present in amygdales in some basalt flows;

(4) some quartzite beds contain chalcocite specks; and

(5) one shale horizon in the formation is weakly cupriferous.

Although the writer has inspected none of these occurrences, the available data suggests that only the type 3 occurrence is primary, and that the other types are the result of supergene leaching and redistribution into porous beds and fractures. The shale horizon (type 5) may have acted as a barrier to local movement of copper charged groundwater.

Carbonate veining and bleaching of wall rocks accompany the cross-fracture deposits, but these phenomena are not necessarily hydrothermal and may also result from supergene processes.

WMC carried out 2 733 m of percussion drilling in areas of geochemical anomalies and known copper mineralization, but few assays were above 0.5 per cent copper (maximum 3.12 per cent over 4.57 m). The occurrences tested were apparently all in cross fractures, and offered some potential for gouging or shallow mining. Diamond drilling totalling 2 215 m (twelve inclined holes) yielded best intersections of 3.20 m assaying 9.02 per cent copper (73 to 76 m depth), and 1.28 m assaying 5.23 per cent copper (112 to 114 m depth), and indicated the persistence of mineralization with depth at only two of the seven localities defined as being of interest following the percussion drilling. Even at these two localities the grade of mineralization decreases with depth despite the replacement of malachite by chalcocite at shallow depth.

In summary, the known deposits only seem to be suitable for gouging operations by individuals. Cupreous ore production took place from 1961 to 1968 and totalled 533.80 t averaging 16.50 per cent copper and in 1966 154.71 t of copper ore averaging 35.46 per cent copper (54.86 t copper) was produced. This copper ore also yielded 39.08 kg of silver. Half the cupreous ore and all the copper ore came from a mine 4.5 km south-southwest of the Warburton Mission, and adjacent to the WMC exploration camp (26°10′00″S, 126°36′00″E). The ore from this mine was in cross-cutting veins, and was worked by aborigines on a tribute basis to WMC from 1966 to 1968. Earlier production of cupreous ore came from several occurrences and was mined by aborigines.

CHAPTER 16

Yilgarn Block

SUMMARY AND CONCLUSIONS

The Archaean rocks of the Yilgarn Block form an area of some 650 000 km^2, nearly eleven times the area of the Pilbara Block to the north. The rock types, tectonic features, metamorphic styles and metallogeny of the two blocks are similar, but the Pilbara Block is probably made up in part of older supracrustal sequences. The southern and northwestern margins of the Yilgarn Block are structural and metamorphic boundaries with the Proterozoic Albany-Fraser and Gascoyne metamorphic 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 has been subdivided into three provinces, the Eastern Goldfields, Murchison and Southwestern Provinces, primarily on the basis of major lithological associations and structural trends (Gee, 1975). The Southwestern Province differs from the other two in having a much greater abundance of felsic gneissic rocks, especially paragneisses, and in having supracrustal rock associations dominated by psammitic to semi-pelitic metasedimentary lithotypes. The grade of regional metamorphism is in the amphibolite to granulite facies over most of the Southwestern Province, whereas elsewhere in the block the metamorphic grade, though variable, is more commonly below the mid-amphibolite facies.

The Murchison Province resembles the Eastern Goldfields Province, but the main structural trend is north to northeast instead of north-northwest, and the supracrustal ("greenstone") belts are arcuate and less continuous rather than linear and extensive. These subdivisions are also of considerable metallogenic importance. Except for one tin field, the Southwestern Province is virtually devoid of known, important base metal deposits or prospects, particularly copper. The Eastern Goldfields Province has accounted for nearly 98 per cent of the total mine production of copper from the Yilgarn Block, though the bulk of production has come from just two areas, Ravensthorpe and Murrin (Table 32). However the largest newly discovered copper deposit is at Golden Grove in the Murchison Province.

The essential components of the Eastern Goldfields and Murchison Provinces are (i) linear to arcuate belts of variably metamorphosed, folded and faulted, supracrustal volcanic rocks (and cogenetic intrusives) and sedimentary rocks, with (ii) intervening, more expansive areas of granitoid and gneissic rocks.

TABLE 32. MINE PRODUCTION OF COPPER FROM THE YILGARN BLOCK

Mine or group	Copper ore and concentrates (t)	Cupreous ore and concentrates (t)	Average grade (%)	Contained copper (t)
1. EASTERN GOLDFIELDS PROVINCE				
a. Ravensthorpe-West River area				
Kundip group	51 990.59		1.83	956.57
Mount Desmond group	102 786.68		15.17	15 592.57
		786.64	11.64	91.59
Mount McMahon group	5 404.22		11.88	642.15
		160.12	8.95	14.33
Ravensthorpe group	34 786.05		7.38	2 567.20
		701.59	11.17	78.37
West River group	197.85		17.07	33.77
		7.11	6.86	0.49
Sundry claims	1 684.31		8.14	137.05
		15.57	10.56	1.64
Sub totals	196 849.70	1 671.03	[1]10.13	20 115.73
b. Murrin area				
Anaconda	47 392.61		9.03	4 277.13
		597.79	7.78	46.52
Nangeroo	1 251.86		19.76	247.25
		210.39	8.39	17.65
Rio Tinto[2]		62.87	10.61	6.67
Sub totals	48 644.47	871.05	[1]9.28	4 595.22
c. Kathleen Valley-Agnew area				
Agnew-Lawlers group	252.08		15.44	38.91
		1 438.71	11.11	159.84
Kathleen Valley group	285.49		12.52	35.74
		2 077.29	11.09	230.25
Sir Samuel group	10.91		14.75	1.61
		166.46	9.41	15.66
Sub totals	548.48	3 682.46	[1]11.39	482.01
d. Remaining areas				
Barrambie	111.67		16.62	18.56
		1 295.07	9.20	119.14
Carterton		66.01	5.13	3.39
Corsair	51.48		13.83	7.12
		29.47	3.48	1.03
Goongarrie	6.22		13.35	0.83
		5.00	5.50	0.28
Higginsville		73.02	9.59	7.00
Jasper Hill		9.24	14.40	1.33
Lady Bountiful		35.15	9.11	3.20
Marda	16.26		5.00	0.81
Mount Ida (Forrest Belle)		7.55	6.90	0.50
Mount Margaret	11.71		20.84	2.44
Mount Pleasant		83.35	7.55	6.29
Paris[3]				191.50
Rowena	2.90		10.00	0.29
Rungine		12.89	8.36	1.08
Wildara		18.20	7.68	1.40
Wiluna gold mine[3]				3.37
Sub totals	200.24	1 634.95	[1]9.52	369.56
Totals	246 242.89	7 859.49	[1]19.98	25 562.52

		2. MURCHISON PROVINCE		
		a. Gabanintha area		
Lady Alma	636.14		7.76	49.35
		953.16	7.10	67.65
Mountain View	310.92		24.27	75.53
		70.31	8.83	6.21
Tumblegum		4 967.20	3.09	153.76
Sub Totals	947.06	5 990.67	[1]5.08	352.50
		b. Remaining areas		
Abbotts		18.16	7.39	1.34
Bunnawarra		8.13	9.20	0.75
Chunderloo	25.16		10.86	2.73
		995.23	2.51	24.98
Day Dawn	56.45		14.57	8.23
		49.00	9.81	4.81
Fields Find	30.94		13.39	4.14
Langs Find	9.50		13.48	1.28
Mount Eelya		6.16	5.05	0.31
Mount Gibson	5.07		22.07	1.12
Mount Mulcahy[2]		49.24	7.19	3.54
Twin Peaks[2]	33.53		17.45	5.85
		55.36	4.73	2.62
Wadgingarra	14.13		7.08	1.00
		2.84	11.30	0.32
Warriedar		2 206.91	9.83	217.00
Sub totals	174.78	3 391.03	[1]7.72	280.02
Totals	1 121.84	9 381.70	5.96	632.52
		3. SOUTHWESTERN PROVINCE		
Netty	3.13		40.90	1.28
		27.37	6.77	1.85
Totals	3.13	27.37	[1]10.26	3.13
Grand Totals	247 367.86	17 268.56	[1]9.83	26 198.17

1. *Weighted average of copper and cupreous ore and concentrates combined.*
2. Official production figures are incomplete.
3. Copper smelted from gold concentrate.

With rare exceptions the contacts between supracrustal and granitoid-gneissic rocks are tectonic or intrusive, the granitoid rocks being younger. Most granitoid rocks are late or post-tectonic and yield radiometric ages in the range 2 600 to 2 700 m.y. Far less common, in general, are syntectonic (deformed) granitoids, migmatites and banded gneisses, though these rock types are commoner in the Southwestern Province of the block, where radiometric ages in the 2 800 to 3 100 m.y. range have been obtained. There is no known copper mineralization of any importance associated with the granitoid, gneissic or migmatitic rock types.

The supracrustal rocks comprise (i) mafic to ultramafic volcanic sequences and cogenetic intrusives, (ii) felsic volcanic complexes, and (iii) clastic sedimentary sequences of volcanogenic and subordinate granitoid provenance. In contrast with the Pilbara Block, poor outcrop, the large distances separating many supracrustal belts, and the lateral facies changes within them, make regional stratigraphic syntheses of dubious merit. Hence a summary of the common lithological associations and cupriferous mineralization is given in Table 33. Successions have been established locally (e.g. Hall and Bekker, 1965; Ross and Hopkins, 1975) in which mafic-ultramafic rocks are prominent low in the sequence, and felsic volcanic and clastic rocks are commonly more important high in the sequence.

The types of cupriferous mineralization present are broadly similar to those in the Pilbara Block, but with some important differences in the Yilgarn Block as follows:

(1) the paucity of lead minerals in copper-zinc deposits and a higher Cu:Zn ratio (mean 2.74 standard deviation 3.37);

(2) the absence of copper-molybdenum or copper deposits in stockworks;

(3) the greater abundance of nickel-copper deposits; and

(4) the rarity of copper-zinc mineralization in calc-alkaline volcanic complexes.

The reasons for these differences are not known, but they relate to some aspects of geotectonic evolution in the Archaean which show regional temporal variations. Considering, for example, the abundance of massive iron-copper-zinc sulphide deposits in calc-alkaline volcanics in the Canadian Archaean Shield, it would seem that crustal evolution processes did not favour either the generation of voluminous calc-alkaline volcanics or the partition of base metals into this environment in the Yilgarn Block. Stratigraphic control could be important also because both the copper-zinc rich, calc-alkaline Whim Creek Group of the Pilbara Block and the Canadian rocks may be younger than equivalent rocks in the Yilgarn Block.

There is no established relationship between mineralization and possible calc-alkaline rocks at either of the two major copper producing areas of Murrin and Ravensthorpe. Regional carbonation is present at Murrin. Here, stratabound iron-copper-zinc sulphides occur at the top of a felsic volcaniclastic metasedimentary unit which is overlain by tholeiitic metabasalt. Cyclic mafic to felsic metavolcanic rocks occur in the area and may be of calc-alkaline affinity, but extrusive and intrusive rocks of komatiitic and tholeiitic affinity also bulk large. Mineralization appears to be extensive at a particular stratigraphic horizon, and there is scope for further investigation especially in the vicinity of Anaconda mine.

At Ravensthorpe, the majority of the copper-gold mineralization is in structural sites within 2 km of the margin of a deformed granodiorite pluton. Though deformed and thoroughly metamorphosed, basaltic to rhyodacitic flows and fragmental rocks are recognisable as hosts, including feldspar-rich rocks of acid to intermediate composition (but not perforce of calc-alkaline affinity). Some mineralization parallels the layering in this sequence, and minor copper-zinc mineralization is known. The widespread occurrence of cobalt-rich pyrite is suggestive of a volcanic exhalative genesis (Appendix 1). Accordingly there are indications that some, but by no means necessarily all, of the structurally located mineralization may be stratabound volcanogenic sulphides mobilized during regional metamorphism.

Much of the recently discovered copper-zinc mineralization, including the Golden Grove and Teutonic Bore prospects, is in (or marginal to) metamorphosed felsic volcanic and/or volcaniclastic rocks which are clearly not developed in mafic to felsic cycles or in calc-alkaline volcanic piles. Monotonous sequences of variably textured rhyolite to dacite pyroclastics and flows (e.g. Golden Grove), or thin horizons of felsic rocks and carbonaceous slate in mafic-ultramafic dominated sequences (e.g. Mount Mulcahy) may both host stratabound copper-zinc mineralization. In medium grade to high-grade metamorphic terrains there is commonly evidence that sulphides have migrated to areas of lower strain such as fold cores, where they may be in bodies elongated parallel to fold plunges and penetrative mineral lineations (i.e. local directions of elongation).

At the same time, much more numerous examples of stratabound but essentially barren, disseminated to massive iron sulphides have been discovered in ostensibly the same geological environments. Supergene enrichment commonly yields gossans assaying around 1 000 ppm or more copper and similar amounts of zinc. Apart from rare sphalerite-rich and rarer chalcopyrite-rich intersections, diamond drilling normally encounters pyrite and/or pyrrhotite containing only trace amounts of chalcopyrite and sphalerite, typically averaging less than 150 ppm copper.

There is much scope remaining for further discoveries of copper-zinc mineralisation (and iron sulphide mineralization) in felsic volcanic environments, but more particularly in the less well exposed parts of the piles which are obviously more difficult and costly to explore. Even so careful evaluation of accessible gossanous outcrops is necessary by geochemical and mineragraphic means, because in some environments, gossans over copper-zinc sulphides may be leached and have abnormally low metal contents. Discoveries made so far indicate that the individual ore bodies or shoots are likely to be small, steeply dipping or plunging, and of complex internal structure and mineral (and therefore grade) zonation. This is partly the result of tectonic and metamorphic reconstitution. Some sulphide bodies are accompanied by massive magnetite units (e.g. Golden Grove) probably reflecting high oxygen fugacity conditions during deposition, and/or desulphurization during regional metamorphism. This feature is of obvious significance in geophysical exploration. The distinctive or critical characteristics of the ore environment remain to be defined. Chlorite-rich wall rocks and coarse fragmental units may occur in association with iron-copper-zinc or just iron sulphides, whether massive or disseminated. Geochemical dispersion haloes and the trace element geochemistry of iron sulphides from barren, copper-zinc bearing or intermediate environments remain to be documented.

Excepting the Ravensthorpe area which may be a special case, cupriferous quartz veins and shears have been of minor importance as mine producers of copper. The majority are in mafic to ultramafic rocks and probably represent mobilization of disseminated syngenetic copper into structural sites during regional metamorphism. The largest deposits in terms of past production are at Gabanintha, Kathleen Valley, Warriedar, Agnew-Lawlers, Paris and Barrambie. Deep supergene enrichment is commonly the determining factor in the economic importance of deposits of this

TABLE 33. MAJOR SUPRACRUSTAL ROCK ASSOCIATIONS AND CUPRIFEROUS MINERALIZATION OF THE EASTERN GOLDFIELDS AND MURCHISON PROVINCES, YILGARN BLOCK

Association	Lithological detail	Mineralization
1. Chert, banded iron formation (BIF) and black slate; interspersed in volcanic sequences	Rock types are intergradational and contain quartz, albite, graphite, micas, Fe-Mg and Ca amphiboles, magnetite, Fe silicates, carbonate and Fe sulphides plus lesser Cu-Zn sulphides; surface silicification is common	(a) Stratiform, veinlet and disseminated pyrite and pyrrhotite is common, but chalcopyrite is sparse and copper values are only enhanced in the oxidized zone; "false" gossans are abundant. (b) Cupriferous quartz veins.
2. Clastic meta-sedimentary rocks, commonly in thick sequences	Polymictic conglomerate, sandstone, greywacke and shale of volcanic and granitoid-gneiss derivation; rare arkose and oligomictic conglomerate	Rare cupriferous quartz veins.
3. Felsic meta-volcanic complexes of limited extent, and rare calcalkaline volcanic centres	Dominantly pyroclastic rocks of sodic rhyolite to dacite composition, some flows and porphyry intrusions; andesite is rare; laterally contiguous volcaniclastic sedimentary rocks are common	(a) Stratabound, disseminated to massive pyrite-pyrrhotite mineralization with minor chalcopyrite-sphalerite is common; major Cu-Zn sulphides are rare, but occur in pyroclastic and volcaniclastic rocks. (b) Cupriferous quartz veins.
4. Mafic to ultramafic metavolcanic sequences and cogenetic intrusive rocks.	Tholeiitic basalt, dolerite and gabbro (Ca-amphibole), komatiitic basalt, dolerite and gabbro (Mg-amphibole), komatiitic peridotite flows, lenses and sills, dunitic dykes and sills, layered intrusions of dunite-norite-gabbro-anorthosite	(a) Abundant cupriferous quartz veins, some with gold. (b) Disseminated and rare massive Fe and minor Cu sulphides. (c) Rare Cu-Ni sulphides in layered intrusions. (d) Common Ni-Cu sulphides in komatiitic peridotite and dunite.
5. Higher grade metamorphic equivalents of 1 to 4	Quartz-magnetite-grunerite (BIF); quartz-feldspar-biotite-garnet-cordierite-andalusite- sillimanite (2 and 3); hornblende-plagioclase, magnesian amphibolite, olivine-talc, actinolite-chlorite (4)	As above, but partial migration and structural relocation of formerly stratiform-stratabound mineralization is common.

type. Some mineralization, especially that poor in quartz, may crop out weakly or be largely blind. It is therefore feasible that small bodies of enriched mineralization may be found by modern prospecting techniques (e.g. Mount Pleasant).

STRATABOUND MINERALIZATION IN SUPRACRUSTAL ROCKS (TYPE A)

COPPER-ZINC DEPOSITS IN FELSIC METAVOLCANIC AND VOLCANICLASTIC ROCKS

MURRIN AREA

History

In this area (Fig. 38), 260 km north of Kalgoorlie, there are three copper-zinc deposits which, in order of decreasing size, are known as the Anaconda (Eulaminna, Mount Malcolm) mine (28°58′10″S, 121°46′00″E), the Nangeroo (Butte City) mine (28°55′50″S, 121°48′20″E), and the Rio Tinto workings (28°55′50″S, 121°45′30″E).

Some 94 per cent of the total mine copper production of 4 595 t of contained copper has come from the Anaconda mine, which together with Nangeroo produced copper ores (which were smelted locally) from 1899 to 1908 and cupreous ores from 1950 to 1967 (Table 32). When the supergene and oxidized ores were largely exhausted in 1908, 75 236 t of pyritic primary sulphides were mined from Anaconda (62 678 t) and Nangeroo (12 558 t) during 1911 to 1922, and railed to Perth for use as a sulphur source in fertilizer manufacture. The copper (and zinc) content of this ore was not recorded, but it was not insignificant as a sulphur content of only 32 weight per cent was noted (pyrite contains 47 weight per cent sulphur). Since 1965 the deposits have been investigated principally by WMC, EZ and Australian Selection (Reynolds and others 1975; Cowan and others, 1975). Williams (1969) has given a petrological account of the host rocks and mineralization at Anaconda.

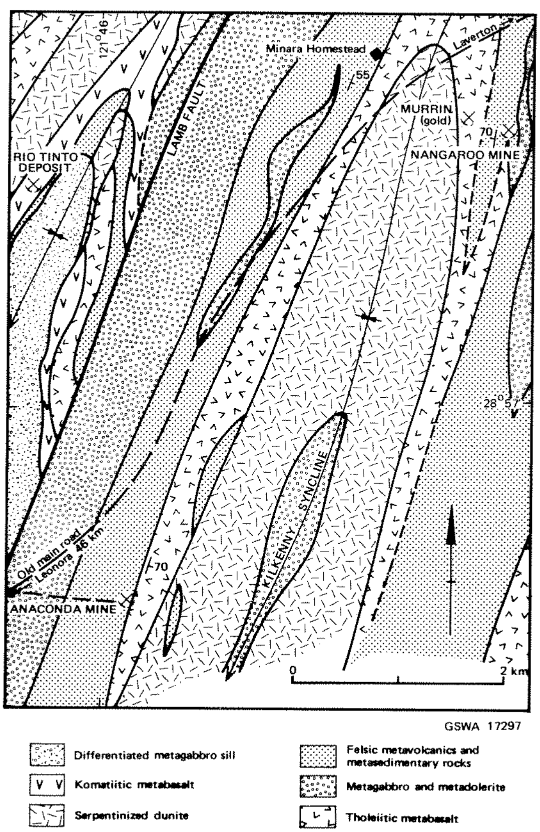

Figure 38. Solid geological map of the Murrin area, slightly modified after Reynolds and others (1975)

Information on the old workings and surface geology at Anaconda is summarized in Fig. 39 (after Woodward, 1908; Clarke, 1925; Hobson and Miles, 1950; Williams, 1969), and known mineralogical zonation in the four mined ore shoots is tabulated in Table 34. Little is recorded about the underground workings at Nangeroo, which are partly confused in the description by Low (1963, p. 158) with the Murrin gold workings situated on a north-northeasterly striking quartz-filled shear, 500 m west of Nangeroo (Fig. 38). A small tonnage of copper ore produced from the Trafalgar lease, 800 m south of Nangeroo is included in the Nangeroo total.

Geology

The Anaconda and Nangeroo deposits are situated at or near the top of a 600 m thick sequence of fine-grained to coarse-grained and rudaceous, poorly sorted volcaniclastic sedimentary rocks, carbonaceous shale, rhyolite, dacite and minor mafic volcanics. This sequence is in turn succeeded by pillowed tholeiitic basalt and both have been intruded by dunitic and gabbroid sills. Though much altered, many of the volcanic rocks in the area appear to have calc-alkaline affinities, and occur in mafic to felsic cycles. The country rocks are statically metamorphosed to low greenschist facies assemblages, thus original textures and structures are preserved in palimpsest by metamorphic minerals. Carbonate minerals are an important constituent of most country rocks, probably as a result of regional metasomatism. A syncline, called the Kilkenny Syncline, plunges gently to the south-southwest. The Anaconda deposit is on the western limb of this structure and the Nangeroo deposit is in a similar stratigraphic position, 6 km to the northeast, on the eastern limb (Fig. 38). A strike fault (Lamb Fault) repeats the syncline to the west, where the Rio Tinto deposit occurs (5 km north of Anaconda) on the west limb of a syncline in a thin felsic tuff unit interbedded in tholeiitic and komatiitic basalt. This horizon is stratigraphically higher than the mineralized horizon at Anaconda and Nangeroo.

Exposure of the mafic metavolcanic rocks is moderate at Anaconda and Rio Tinto, the metasedimentary and felsic volcanic rocks are generally poorly exposed, and surface outcrop is very poor at Nangeroo.

Mineralization

At Anaconda mineralization occurs over a 430 m strike length in four shoots dipping east-southeast at 45 to 75 degrees which, as indicated by the underground workings and subsequent drilling, are as follows:

(1) northern shoots: (i) a shoot dipping steeply east and pitching steeply to the northeast below the north open cut, and (ii) a shoot,

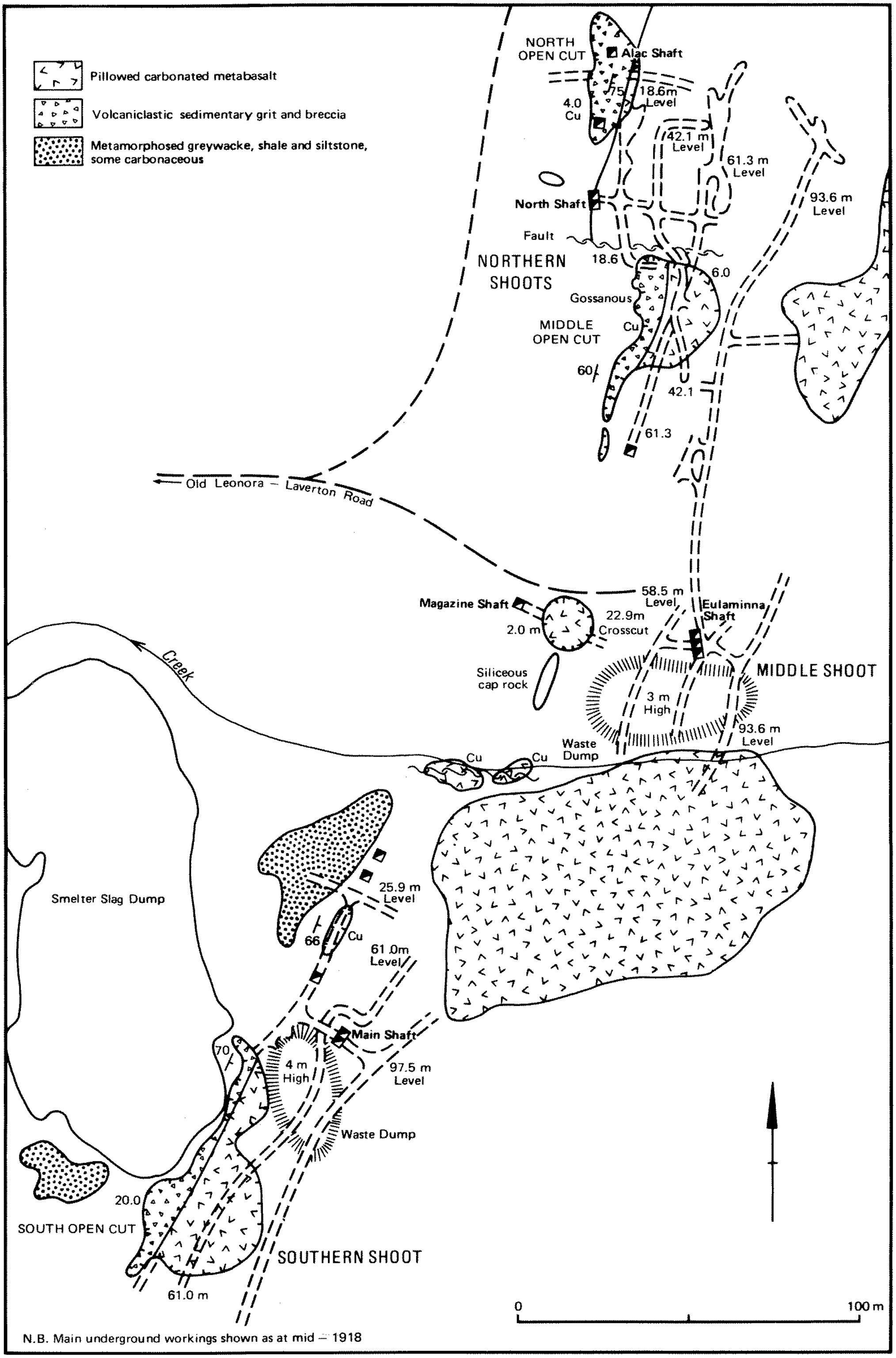

Figure 39. Anaconda copper-pyrite mine workings

probably bounded by an easterly fault at the northern end of the middle open cut, which dips steeply east and pitches to the south;

(2) middle shoot dipping consistently at 45 to 50 degrees to the east below the Eulaminna shaft and pitching steeply southwards;

(3) southern shoot with a similar orientation to middle shoot but occurring below the south open cut.

At the surface, copper mineralization in the form of staining and secondary veinlets is restricted to the area north of the Main shaft, the middle and north open cuts, and small outcrops of strongly fractured metabasalt in the creek. A copper-stained, limonitic gossan is visible on the western side of the middle open cut. The bulk of the rock on the two main dumps is barren metasedimentary country rock, pyritic black shale and pyritic volcaniclastic breccia. Immediately north of the north open cut, there is an outcrop of fresh, undeformed felsic tuffs.

Mineralization in the three open cuts is associated with a lenticular unit of sedimentary grit to breccia consisting of angular to rounded clasts of felsic volcanics, siltstone, black shale and massive sulphide (commonly pyrite) set in a lithic, chloritic matrix of similar composition. This has been confirmed by inclined diamond drilling undertaken by EZ in 1969, in the case of the southern shoot and the northernmost shoot. In the southern shoot two mineralized zones, 0.3 to 2.6 m thick and about 6 m apart in drill core, were intersected in three drillholes at 100-110 m vertical depth, with the uppermost zone being at the breccia-metabasalt contact. The copper:zinc ratios are variable, but zinc is more abundant in the upper zone which contained the best intersection, 2.6 m assaying 4.7 per cent copper and 4.2 per cent zinc. The mineralization consists of massive pyrite and lesser iron-bearing sphalerite and chalcopyrite with chlorite and calcite gangue (Williams, 1969). The host breccia contains some disseminated pyrite and traces of sphalerite and chalcopyrite.

Two of three drillholes in the northernmost shoot encountered similar mineralization in sedimentary breccia and siltstone at about 120 m and 175 m vertical

TABLE 34. MINERAL ZONATION AT ANACONDA MINE

Ore shoot	Depth (m)	Mineral zonation	Copper grade (%)	Remarks
Northern (two shoots)	0-30.5	Cuprite native copper chrysocolla	Low	Diamond drill core contains pyrite, sphalerite in primary zone.
Middle	0-30.5	Chrysocolla, cuprite, native copper	Low	
	30.5-43.3	Massive chalcocite and pyrite	30-35	
Southern	0-39.6	Malachite, azurite Fe oxides in siliceous matrix	15-25 and to 40, above water table	Contains minor gold and silver.
	WATER TABLE—27 m			
	39.6-58.5	Chrysocolla, cuprite, native copper in Fe oxides and chalcedony		
	58.5-76.2	Bornite, chalcocite, pyrite, sphalerite	1-10	
	76.2-93.6	Pyrite, minor chalcocite and asbolite.		Worked for pyrite only.

depths, assaying 2.13 per cent copper and 9.56 per cent zinc over 7.16 m, and 1.86 per cent copper and 6.5 per cent zinc over 5.79 m respectively. In the latter intersection (vertically below the other), Williams (1969) described a chloritic footwall rock containing sulphides increasing in amount upwards, and the presence of sympathetic copper-zinc abundances in the lower part of the mineralized zone, whereas concentrations of the metals are antipathetic in the upper part. In the rock these effects are partly represented by fine-scale mineralogical layering. Variably recrystallized relict colloform textures and cross cutting quartz-carbonate-pyrite veins are also described by Williams (1969) from the three separate drill core intersections he examined.

Three widely spaced drillholes put down between the northermost and the southern shoot failed to encounter either sedimentary breccia or important widths of copper-zinc mineralization. A coincident geochemical and magnetic induced polarization anomalous zone 450 m north of the mine area was also drilled by EZ, and found to correspond to disseminations and veinlets of pyrite in greywacke, siltstone and shale.

At Nangeroo the mineralized area is some 400 m long north-south and an average of 75 m wide in plan. Apart from some small siliceous gossans, there is very little outcrop in the area. Weathering is pervasive to a depth of 30 m (water table) especially close to mineralization because of the breakdown of sulphides to limonite, azurite, malachite and para-atacamite. A major diamond-drilling programme undertaken by Australian Selection has defined a complex, interfingering stratigraphy, similar to that at the Anaconda area, but with a more conspicuous felsic volcanic element and rapid facies changes (Cowan and others 1975, p. 80). Thin, but relatively persistent basalt units are interbedded with dominantly pyroclastic felsic volcanic rocks, tuffaceous sedimentary rocks, sedimentary breccia and carbonaceous shale. The dip is about 70 degrees to the west.

Massive fine-grained to coarse-grained recrystallized pyritic sulphides, containing very variable amounts of pyrrhotite, iron-bearing sphalerite and chalcopyrite, and some combined silver, occur in four small shoots up to 4 m thick and 300 m long. The pyrite is cobalt rich, sphalerite is a low-cadmium variety, and trace amounts of selenides occur in the massive ore. Cassiterite may be a common accessory. Some mineragraphic data are given in Appendix 1. These shoots plunge north at about 20 degrees, and are situated at or near the top of felsic units where overlain by mafic volcanic horizons, at several stratigraphic levels. Chloritic wall-rock alteration accompanies some shoots. The massive sulphides may be layered parallel to the host rock layering, or be more isotropic and irregularly layered due, in part, to recrystallization. Chalcopyrite veinlets cut the massive ore. Angular to sub-rounded fragments of identical massive sulphides are found in sedimentary to volcanic breccia which occurs as lenses overlying, underlying or laterally contiguous with, massive sulphide shoots.

Copper:zinc ratios are very variable but appear to average about 0.5 for massive and disseminated sulphides. The best intersections of copper-rich massive sulphides assayed 14.1 per cent copper, 2.6 per cent zinc over 3 m and 14.7 per cent copper and 9.5 per cent zinc over 6 m, and occur in the longest shoot, which coincides with the exposed gossans and the line of old mine workings. Small shoots of zinc-rich iron-copper sulphides have also been discovered in the same contact zone 2.4 km south of Nangeroo at Crayfish Creek prospect.

The Rio Tinto deposit is a small zinc-rich massive sulphide body situated at the top contact of a thin felsic tuff, lava, volcaniclastic sedimentary and carbonaceous shale unit in a mafic volcanic sequence. Six diamond drillholes put into the deposit by Australian Selection encountered only minor intersections of iron-zinc-copper sulphides.

The Pearl Shell Well occurrence (28°51′40″S, 121°45′50″E) is a small, fragmentary copper-stained gossan in a pit in felsic volcanic rocks 1.5 km northwest of Pearl Shell Well and just south of the new Leonora-Laverton road. Percussion drilling by Australian Selection encountered no mineralization. The Welcome Well West occurrence (28°49′10″S, 121°39′20″E) is similar and also yielded negative results from percussion drilling.

Conclusions

Reynolds and others, (1975) noted that the copper-zinc deposits in the Murrin area have some features in common with massive sulphide deposits in the Canadian Shield (Sangster, 1972). However the deposits of Murrin appear to be distal from an ore fluid source if this is linked to an exhalative volcanic fissure. As at the Whim Creek copper-zinc deposit, it is not clear to what extent the chlorite-rich wall rocks, which may accompany mineralization at Murrin, are a function of original rock composition, wall rock alteration or metasomatic reaction during regional metamorphism. The cobalt-rich nature of the pyrite, and the presence of selenides and cassiterite at Nangeroo are consistent with a volcanogenic origin.

The breccias which are host to much of the mineralization contain an important volcanic element and have evidently formed more or less *in situ* with only very limited transport. In part, these breccias clearly represent fragmented, stratiform massive sulphide mineralization, and are intimately related spatially to the massive shoots in most places. It is concluded therefore that subaqueous gravitational slumping has produced the breccias. This was followed by additional precipitation of stratiform sulphides in some locations to form a capping of massive ore, perhaps as a result of the movement of heavier-than-sea-water metalliferous brines into the same seafloor depressions that trapped the slump breccias.

The prospective horizon on the eastern limb of the Kilkenny Syncline has been tested at shallow depths. Systematic percussion drilling of the western limb would seem to have a good chance of locating further mineralized areas, because poor exposure conceals this apparently extensively mineralized stratigraphic level. At Anaconda, the middle shoot has not been adequately tested at depth, and the northern shoot remains open at depth to the north. The southern limit and down dip extent of the southern shoot remain unknown. Further diamond drilling is clearly warranted here.

TEUTONIC BORE PROSPECT

The Teutonic Bore copper-zinc prospect (28°24′50″S, 121°08′30″E) is 55 km north-northwest of Leonora and 1.8 km southwest of Teutonic Bore. The prospect occurs on the western margin of a poorly exposed zone of felsic metavolcanic rocks extending some 70 km in a north-northwest direction. This zone is intruded by biotite granitoids to the east, and is structurally overlain by mafic and ultramafic metavolcanic rocks to the west. Foliated quartz-sericite schists representing deformed and metamorphosed dacitic-rhyodacitic ash and lapilli tuffs, agglomerates and subordinate flows, strike 340 degrees and dip at 60 to 70 degrees westwards. The foliation appears to be subparallel to the layering. Rapid lateral and vertical grainsize changes are typical, and are well seen in a ridge of weathered pyroclastic rocks running east of the prospect which occurs in a mulga (*Acacia sp.*) flat. Locally areas with voids or limonitic pseudomorphs after pyrite are common in this ridge.

Gossanous material geochemically anomalous in base metals occurs as matrix disseminations, veinlets and massive, stratabound bodies in the felsic pyroclastic sequence. The main drilled gossan is of the latter type situated near the structural and probable stratigraphic top of the sequence in highly altered mafic rocks. At this gossan, thirty inclined diamond drillholes sunk by Australian Selection in 1976-1977 have defined a lens of massive and disseminated iron-copper-zinc-lead sulphides up to 50 m thick. The main deposit is 320 m long and the massive sulphides are a maximum of 25 m in thickness. The primary sulphides are pyrite, sphalerite, chalcopyrite and galena which are weathered to 80 m depth, although the water table now stands at 40 m. Chalcocite occurs above 80 m depth. The best intersections are from the central and thickest part of the lens, for example, 19.3 m (true width) assaying 6.7 per cent copper and 15.9 per cent zinc. The mineralization appears to pinch out at depth (about 200 m) as well as laterally. In mid-1977, the operators published an estimate of resources of between 2 and 3 Mt averaging 3.5 per cent copper and 9.5 per cent zinc, plus 150 g/t silver.

To the south, in the same broad mineralized zone, the dissemination-veinlet type of gossan has been found to correspond to minor amounts of disseminated pyrite, sphalerite, galena, chalcopyrite and tetrahedrite in foliated felsic pyroclastic rocks.

Evidently more continuous massive mineralization needs to be found for this prospect area to be of sustained economic interest in itself.

WATTAGEE WELL PROSPECTS

Since 1969, several copper-zinc-lead anomalous gossans have been examined by Kennco, Eastmet and Esso in a 6-km-long, north-northeast striking belt of low ridges to the west of Wattagee Well (ca. 27°12′30″S, 117°52′00″E). The mineralized horizons are fine-grained quartz-muscovite (-chlorite) phyllite or schist, some of tuffaceous aspect, and carbonaceous phyllite. These rocks are a minor component of a sequence of quench textured feldspathic metabasalt, and amygdaloidal pale coloured metabasalt, all intruded by metagabbro. Poorly exposed fragmentary gossan outcrops can be traced discontinuously over 400-m strike-length, and with the assistance of induced polarization and INPUT geophysical methods can be extended a further 1 km along strike. In the north drilling has encountered only massive pyrrhotite, impoverished in copper and zinc. In the south, zinc-rich mineralization (up to 7.5 per cent over 3 m) averaging less than 0.5 per cent copper has been found by Esso in a percussion-diamond drilling programme testing a 1.4 km long, anomalous zone. Eastmet intersected a 6 m wide zone assaying 0.7 per cent copper in 1970, also in the southern part of the area.

EELYA NORTH PROSPECT

This prospect (27°18′20″S, 118°07′30″E) is in very poorly exposed, nearly flat terrain strewn with vein quartz rubble. Feldsparphyric, flow banded rhyolite, coarse sericite-magnetite schist, quartz-feldspar-dark amphibole rock, metadolerite and metagabbro are present in the area, which is evidently very heterogeneous lithologically. The strike is east-northeast and dips are steep. A 50-m-long gossan in the felsic metavolcanic rocks has been drilled by EZ, yielding a best intersection in drill core of 1.3 m of 2.4 per cent copper and 0.22 per cent zinc from massive pyrrhotite-pyrite-chalcopyrite mineralization.

GOLDEN GROVE PROSPECT

Introduction

The Golden Grove copper-zinc-silver prospect (28°46′40″S, 116°57′50″E) is some 480 km north-northeast of Perth, and 1 km west of the Paynes Find-Yalgoo road. The site of the coincident gossans, also known as "Gossan Hill", is a prominent isolated hill of weathered felsic metavolcanic and related sedimentary rocks rising above the plain. The deposit was discovered in early 1971 by J. Phillips and J. N. Pitt (Aztec Exploration Pty. Ltd.), who optioned the tenements to Amax in early 1972. In mid-1973 EZ entered the joint venture and took charge of the exploration programme. Indicated resources of 13.5 Mt averaging 3.59 per cent copper (at 1 per cent cut-off) have been announced, based upon the seventy-seven diamond drillholes completed which total 43 440 m. This description is based on field observations and accounts by Rutter (1972) and Frater and Roark (1976).

Geology

The regional geological setting of the prospect is shown in Fig. 40, which is adapted from Muhling and Low (1973). The prospect is on the eastern limb of a synclinorial structure plunging gently towards the south-southeast. The core of this structure is occupied by medium-grained to coarse-grained and conglomeratic, clastic metasedimentary rocks. These rocks unconformably overlie a thick sequence of fine-grained to medium-grained clastic metasedimentary rocks, which includes chert, jaspilite or banded iron formation in the upper part, and metamorphosed lensoid felsic volcanic-volcaniclastic complexes in the lower part. Golden Grove prospect occurs in the proximal section of one such felsic volcanic complex. The equivalent lower part of this sequence on the western limb of the synclinorium appears to have been largely removed by the emplacement of granitoid rocks (Fig. 40).

The volcanic complex at Golden Grove is presumed to face west, and is about 800 m thick. The layering strikes about 310 degrees and is subvertical, and is cut by a subvertical, lensoid or double foliation striking from 320 to 345 degrees. Leucocratic adamellite and granophyre containing rounded phenocrysts (up to 5 mm) of quartz have intruded the complex in the east. Euhedral, rounded or lensoid quartz phenocrysts (relict β quartz) or megacrysts up to 3 mm in size also characterize the felsic volcanics present at Gossan Hill. These rocks are predominantly rhyolitic to dacitic in composition, and range in grain size from ash tuff to lapilli tuff, less commonly, to agglomerate. The felsic volcanic rock is quartz, sericite, chlorite, pyrite, carbonate, of which 75 per cent is commonly quartz, except in the mineralized part of the sequence. Rapid lateral and vertical changes in grain size and lithology are typical, but there is a tendency for the grain size to decrease upwards (westwards) and along strike from Gossan Hill. This is accompanied by more marked development of bedding and probably a change in part from volcanic to volcaniclastic elements. These features imply that Gossan Hill is proximal to a volcanic centre.

The Gossan Hill sequence recognized by Frater and Roark (1976) is as follows:

Top (west)	8. "Volcorudite" (coarse lithic lapilli tuff)	
	7. Hanging wall quartz-eyed "volcarenite" (lithic tuff)	30-40 m
	6. Hanging wall chert	10-15 m
	5. Lode horizon	100 m
	4. Footwall lapilli tuff	80 m
	3. Lower cherty tuff	30 m
	2. Footwall quartz crystal lithic tuff	180 m
Base (east)	1. Basal tuff	200 m+

Altered dacite, porphyritic dacite and dolerite dykes and sills have intruded this sequence. The volcanic rocks are cream weathering in outcrop but are grey

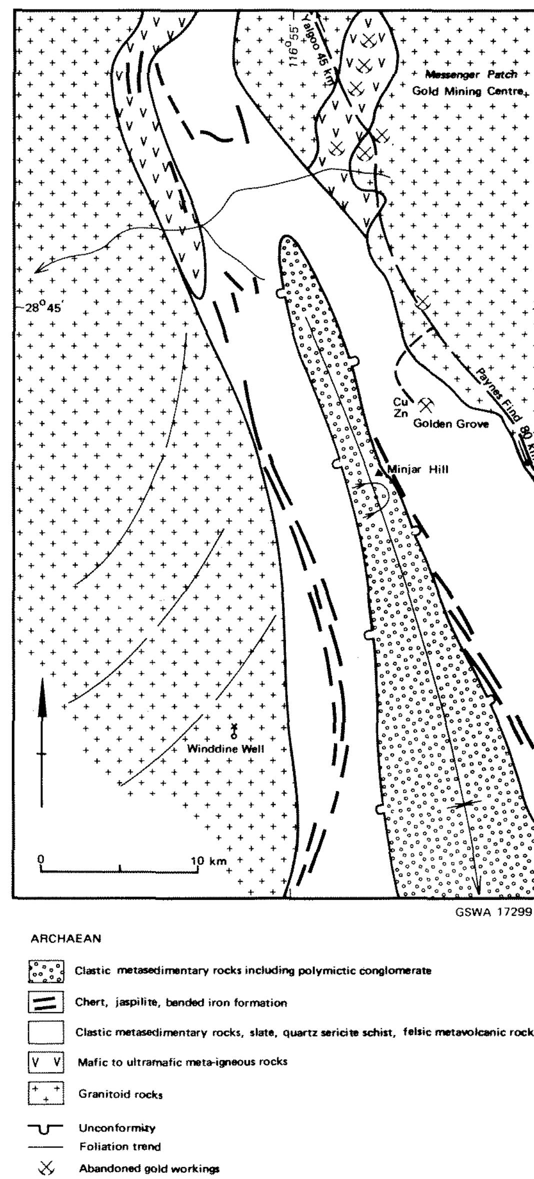

Figure 40. Regional geological setting of the Golden Grove copper-zinc prospect

green where fresh. The footwall lapilli tuff and lode horizon are purple red-brown weathering and green where fresh because of the presence of abundant chlorite (iron and magnesium rich varieties). Spotty silicification characterizes some of the footwall rocks and the lode horizon. Frater and Roark (1976) note that the lode horizon is particularly heterogeneous lithologically, consisting of lithic and crystal tuffs, chlorite schist, chert, massive magnetite and sulphides. Fine-grained, dense, hematite gossans developed over massive magnetite are conspicuous in outcrop on the summit of Gossan Hill, and are accompanied by less prominent, porous, red-brown layered goethite gossans after massive sulphides. The gossans are surrounded by red fissile rocks which are the weathered equivalent of chlorite schist.

Mineralization

The mineralized zone at Gossan Hill is within the lode horizon. The zone is discoid in shape, 550 m long at the surface and 70 to 130 m wide, and though irregular in detail is broadly conformable with recognizable layering. Several sulphide-magnetite ore shoots up to 70 m thick occur within this mineralized zone, and are broken up by dacitic and doleritic intrusives and by faulting. Weakly mineralized or pyritic chlorite schist separates the shoots. Mineralization has been encountered down to 400 m below surface, but here the zone is only 150 m long and 90 m wide. Faults appear to terminate the zone to the north and south, but small appendages of mineralization occur immediately beyond these faults.

The primary mineral assemblage is pyrite-magnetite-chalcopyrite-pyrrhotite (hexagonal and monoclinic) plus subordinate sphalerite, minor galena and trace amounts of arsenopyrite, cubanite, tennantite, valleriite, pentlandite and tellurobismuthite. The gangue mineralogy is quartz, magnesium and iron chlorites, talc and dolomite. Malachite, and minor azurite, chalcocite and covellite occur in the oxidized zone.

Metal zonation is complex, but the mineralized zone has a copper-rich centre in the lode horizon, with the amount of zinc and lead increasing both upwards and laterally. The zinc-rich mineralization is mainly in the hanging wall chert and though laterally more extensive than the copper mineralization it is poddy and discontinuous. Magnetite is the most abundant mineral in the ore shoots; it forms massive or foliated lenses commonly 30 to 40 m thick which contain little sulphide (typically pyrite), except marginally where several metres of foliated or vein-like pyrrhotite-chalcopyrite-sphalerite-galena occur. The primary metal zonation has evidently been complicated by the local redistribution of sulphide-oxide minerals according to individual mineral strengths, during deformation and metamorphism. Marginal brecciation of magnetite-pyrite aggregates illustrates their greater strength and consequent brittle deformation. The magnetite-rich parts of the shoots are more continuous than the sulphide-rich parts. Some magnetite seems to be secondary as it forms rims around sulphide grains in a chlorite matrix.

Genesis

Though the internal structure, metal zonation and geochemistry of the mineralized zone have probably been partly modified by deformation, regional metamorphism and sulphide-silicate reactions, the prospect has the hallmarks of a volcanogenic massive sulphide deposit. This deposit was emplaced at the top of a volcanic cycle (terminated by the hanging wall chert) within a felsic volcanic pile of apparently monotonous chemical composition. The textures of the host rocks indicate proximity to an explosive, eruptive centre but this was not necessarily coincident with the source of the ore fluids. The abundance of magnetite suggests that a high oxygen fugacity prevailed during precipitation of the iron-copper-zinc fluids. At the same time, considerable alteration of the wall rocks probably took place with the addition of iron and magnesium being expressed by the abundance of chlorite and to a lesser extent talc. If these rocks were originally lithologically like the rest of the felsic volcanic sequence, such alteration would involve the loss of alkalis and silica in particular.

MOUNT MULCAHY DEPOSITS

Some 5 km east of Glen Homestead are two gossan localities (ca. 27°03′30″S, 117°42′00″E), 750 m apart, situated within a thin metasedimentary and tuffaceous horizon in a mafic meta-igneous sequence. This sequence comprises mainly pillowed tholeiitic metabasalt succeeded by a layered gabbroid complex. These rocks are involved in a boat-shaped, east-plunging syncline with an axial surface dipping 65 degrees northwards. The known mineralized area is on the southern limb, near the hinge of the syncline, where the metabasalts overlying the mineralized horizon form a distinct break of slope.

At the western of the two localities, massive copper-stained limonitic gossan occurs in two patches 60 m by 10 m and 40 m by 10 m, representing separate, small ore shoots plunging to the north-northwest. Shafts about 7 m deep have been sunk on each gossan (developed over a 1.5 m thick limonite vein in one case), and a small tonnage of cupreous ore was produced from 1954 to 1965 (Table 32). The host rocks are finely laminated cherty metasedimentary rocks, quartz-sericite phyllite, black shale, and silicic metavolcanic rock, and the mineralization occurs at or close to their contact with overlying metabasalt.

Some shallow pits have been dug on the gossans at the eastern locality, smaller gossans crop out over 250 m strike length. Chrysocolla stains and coatings are common in some gossans, and there are lenses of vein quartz closely associated, which point to some mobilization or ore, but without wall-rock alteration. A fine mineral lineation plunging at 25 to 30 degrees towards 350 degrees is visible in the metasedimentary and overlying metabasaltic rocks.

The favourable contact zone was prospected during 1969-1972 by the Union Oil—Hanna—Homestake consortium, which found sporadic mineralization along 9 km of contact using surface geochemistry and systematic percussion drilling (186 holes totalling 4 248 m). Follow-up diamond drilling (34 holes totalling 4 178 m) was concentrated at the eastern gossan locality, where massive sulphides were defined forming a body plunging towards 335 degrees in a plane dipping 40 degrees towards 030 degrees at the surface, but flattening with depth and pinching out some 150 m down dip. The massive sulphides are 65 to 70 per cent pyrrhotite (monoclinic), plus chalcopyrite, sphalerite and minor galena and pyrite. The mineralization is zoned, being zinc rich in the upper section. Disseminated or veinlet sulphides, in which pyrite may predominate, underlie the massive sulphides. The best intersection (30 m down dip from the surface outcrop of the gossans) was an 8.84 m drilled width assaying 7.9 per cent copper, 6.80 per cent zinc, 0.50 per cent lead and 58 g/t silver. Using a high cut-off figure of 2.5 per cent copper, and a minimum true thickness of 1.52 m for the mineralized sections, drill indicated reserves were calculated at about 250 000 t averaging 3.77 per cent copper and 2.75 per cent zinc, plus unstated but possibly significant values of silver, lead and gold.

Barren iron sulphides were found by WMC in 1972-1974 in a lower metasedimentary horizon in the mafic-volcanic pile on the southern limb of the syncline. Copper assays of pyrrhotite-pyrite sulphides in black slates were less than 350 ppm.

There are several analogies between the Mount Mulcahy mineralized environment and that in the Kilkenny Syncline at Murrin. Although known shoots are small, they may be high grade, and the mineralized contact is worthy of more detailed subsurface exploration.

RUNGINE DEPOSIT

This small occurrence (32°08′10″S, 121°41′10″E) is similar to Mount Mulcahy in that a cupriferous tuffaceous black slate unit is interbedded in a dominantly mafic sequence. Deformed, laminated quartz-limonite-malachite-azurite mineralization occurs as concordant lenses up to 2 m wide on the western side of the slate unit, which is 25 m thick and dips at 75 to 80 degrees to the east. Gossanous material was noted over a 250 m strike length, and several pits have been dug over 150 m of this length. A small tonnage of cupreous ore was produced in 1953 (Table 32). The deposit appears to be of no economic importance.

DEPOSITS IN METASEDIMENTARY ROCKS UNRELATED TO FELSIC VOLCANISM

DIEMALS PROSPECT

This prospect (29°36′S, 119°09′E) consists of a small, siliceous copper gossan and ferruginous zones developed in a 150 m thick pelitic metasedimentary unit in a mafic intrusive and extrusive sequence which strikes north. The mineralization occurs at the contact between graphitic slate and metabasalt, and probably represents supergene enrichment of iron sulphides in the slate, although some copper may have been derived by leaching from the metabasalt. The best result of 514 vacuum drillholes and 18 percussion drillholes put in by WMC was 4.57 m assaying 4.23 per cent copper and 1.30 per cent zinc.

MOUNT ALFRED PROSPECT

The Mount Alfred prospect (28°49′30″S, 119°59′30″E) occurs in a layered sequence of quartz-feldspar-chlorite schist, graphitic slate, chert, banded iron formation and mafic meta-igneous rocks in a narrow, north-striking supracrustal belt. A thin unit of chlorite-malachite schist assaying up to 19 per cent copper is associated with laminated pyritic meta-siltstone and a magnesite cap rock both of which assay up to 1 to 4 per cent copper. The surface geochemical anomaly defined by Australian Selection measured only 50 m by 2 m, and it was concluded after drilling that the occurrence was supergene in origin and of no economic significance.

DEPOSITS IN MEDIUM-HIGH GRADE METAMORPHIC ROCKS

INTRODUCTION

The mineralization described here is in deformed and recrystallized rocks which generally lack primary textures diagnostic of origin. In some cases the mineralization has been partly mobilized out of an originally stratabound location. In common with the host rocks the structure of mineralized zones may be complex (e.g., folded, rodded and boudinaged). In most examples the host rocks are probably derived from volcanic or volcaniclastic rocks of felsic composition. The deposits are described from north to south.

CHUNDERLOO MINE

The Chunderloo (Yaloginda) copper mine (26°42′30″S, 118°21′50″E) is 7 km southwest of the Yaloginda gold mining centre. Following Gabanintha and Warriedar, the Chunderloo mine has been the third largest producer of cupreous ore in the Murchison Province (Table 32). Production proceeded from 1955 to 1962 and amounted to 955 t averaging 2.51 per cent copper; gold was also extracted from the ore. The bulk of the higher grade cupreous ore probably came from the open cut (Fig. 41). In 1917 and 1944 25 t of copper ore averaging 10.86 per cent copper was mined.

The mine occurs in lineated and foliated amphibolites and subordinate quartz-muscovite-chlorite-hornblende schist which strike north-northeast and form the western, granitoid-veined margin of a supracrustal belt extending to Meekatharra and beyond. The mineralization is in the form of a 5 to 50-cm-thick, stratabound goethite-chrysocolla-malachite-azurite-cuprite-quartz lenticular horizon, which is confined to

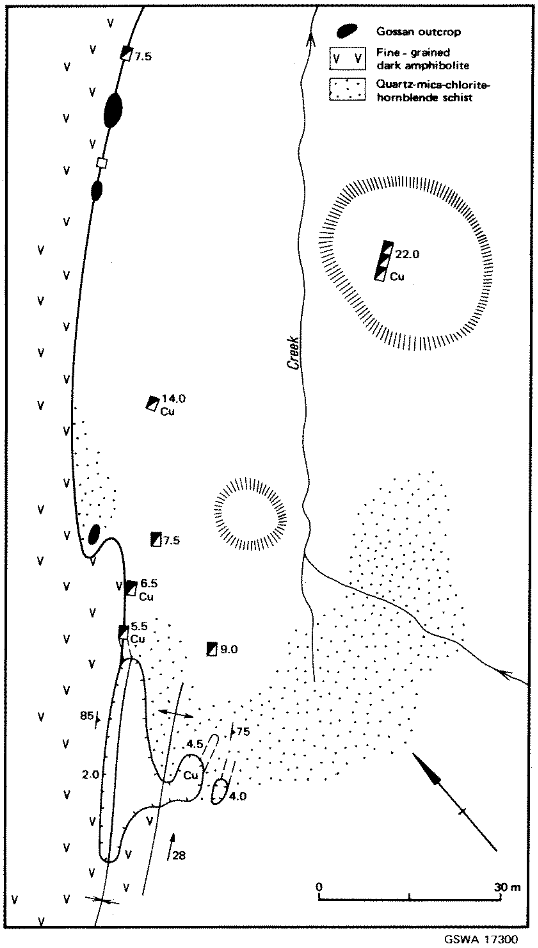

Figure 41. Surface plan of Chunderloo mine

a folded and lineated contact between fine-grained dark amphibolite and structurally overlying fine-grained, layered quartz-mica-chlorite-hornblende schist (Fig. 41). Cupriferous quartz-goethite veinlets are present in fractures oriented normal to the strong mineral lineation. This lineation is congruent with moderately appressed asymmetrical similar folds that plunge at 20 to 30 degrees towards 044 degrees. The stratabound mineralization may be thickened 2 or 3 times in these fold hinges, and appears to be sited about 1 m above the amphibolite-schist contact.

The deposit is similar to Yannery Hill mine (West Pilbara region) but on a smaller scale. However if supergene enrichment has occurred over a large enough area down dip from the surface workings, the remaining mineralization could be amenable to a small open-pit mining operation like that recently undertaken at Whundo in the West Pilbara.

BUNNAWARRA PROSPECT

A few tonnes of cupreous ore were produced in 1960 and 1964 (Table 32), from Bunnawarra (Edamurta) prospect (28°34′10″S, 116°29′00″E) which is located 9.5 km at 297 degrees from Bunnawarra homestead. The workings consist of pits and shallow open cuts up to 3 m wide which have been excavated over a 300 m strike length. The host chlorite schist contains copper-stained quartz veins and thin mineralized zones in limonite-cemented vein quartz breccia. This visible mineralization is essentially stratabound in a thin sequence of steeply northwest-dipping, laminated quartzite, chlorite-quartz-sericite schist, quartz-chlorite-garnet-amphibole rock. This sequence is complexly deformed and structurally overlies strongly deformed granitoid rocks forming low relief terrain to the east, and is in turn overlain by metadolerite and metagabbro forming hilly terrain to the west. In the schist sequence crenulation lineation and folds plunging down dip, deform a gently southwest plunging mineral lineation.

The prospect was investigated by Unimin from 1973 to 1975 who identified disseminated hematite-goethite, copper-zinc anomalous material in quartz-sericite breccia, quartzite, garnet-quartz-chlorite schist and lapilli-textured felsic rock in a stratabound zone 1.5 km long, but best developed over 700 m with a maximum width of 100 m. Inclined diamond drilling (totalling 2 618 m) in this zone has indicated that mineralization in a structurally higher quartz-sericite breccia and sericitic quartzite is zinc-rich consisting of sphalerite and pyrrhotite with only minor chalcopyrite. Mineralization in a structurally lower quartz-chlorite-sericite-(garnet) schist and quartzite consists of pyrrhotite-chalcopyrite-sphalerite bearing breccia, veinlet, stratiform and disseminated sulphides (Appendix 1), which returned a best intersection of 3.8 per cent copper over a drilled width of 3.15 m. There appears to be insufficient mineralization present to be of economic interest: massive sulphides are lacking. The surface expression of the mineralization is apparently a faithfull reflection of the thin zones of disseminated sulphides encountered at depth.

FREDDIE WELL PROSPECTS

The Freddie Well zinc-copper prospects (ca. 28°45′00″S, 118°40′50″E) are 1 to 3 km west of Freddie Well and some 20 km southwest of the abandoned Youanmi townsite, at the southwestern margin of a metamorphosed layered gabbroid complex. A north-northwest-striking zone of foliated and lineated quartz-sericite-(chlorite-feldspar) schist up to 500 m wide, is interposed between the gabbroid complex to the east and largely laterite covered granitoid rocks in a plateau to the west. The schist contains thin horizons of folded, fine-grained to medium-grained, layered quartz-sulphide (-magnetite) rock near its eastern margin, which have been intruded and partly ingested by fine-grained to coarse-grained, statically recrystallized metagabbro. The quartz-sulphide rock, known locally as "freddite", is a facies variant of metamorphosed banded iron formation (quartz-magnetite rock), and is characterized by opalescent blue quartz grains charged with rutile inclusions, which are enclosed in a matrix of pyrrhotite, pyrite (cobalt-rich), sphalerite, chalcopyrite and magnetite (see Appendix 1). Up to 50 per cent sphalerite occurs in some mineralized lenses. Mineralization is also present as a matrix to a breccia of schist, opalescent quartz and metagabbro. Weathering is shallow, as sulphides may be found at 10 to 12 m depths and many gossans carry box works. More hematitic gossans develop over massive titaniferous and vanadiferous magnetite bands in the gabbroid complex.

Exploration by a consortium of Geometals, Carr Boyd, Conwest and Westralian Nickel in 1970-1972, and by CRA in 1974-1976 has indicated resources of about 500 000 t averaging 10 per cent zinc and 0.25 per cent copper in "A zone" and "D zone". The main deposit is at "D zone" where two parallel shoots 8 m apart are 120 m long and 5 to 6 m wide, and strike north-northwest along the schist-gabbro contact. The "A zone" is 1 500 m to the south and is a folded inclusion entirely within metagabbro. It is less than 10 per cent of the size of the "D zone" mineralization but contains copper intersections up to 1.21 per cent over a 1.83 m drill core length. Zinc assays from both zones average from 5 to 22 per cent over the mineralized intersections. The virtual absence of lead from the sulphide assemblage is notable.

Smith and others (1976) have commented that the projected southern extension of the prospective schist-gabbro contact below the laterite plateau remains to be tested.

YUINMERY PROSPECTS

A series of copper prospects (ca. 28°35′S, 119°54′E) associated with metamorphosed chert, banded iron-formation and felsic pyroclastic rocks structurally overlying tholeiitic metabasalt, occurs in a major synformal structure 8 km east-northeast of Youanmi townsite (abandoned). This structure closes southwards and has a north-striking axial surface which crosses the Youanmi-Sandstone road. Metagabbro and granophyre intrude the sequence, which occurs in a separate supracrustal belt from that containing the Freddie Well prospects.

The area has been prospected by WMC from 1969 to 1976 who located widespread, low-grade, pyrite-pyrrhotite-magnetite-chalcopyrite mineralization in chloritic felsic metavolcanic rocks (largely pyroclastic) and recrystallized chert and banded iron-formation, commonly intruded by granophyre. Most mineralization is disseminated, but thin zones of massive iron sulphides have been intersected in drill core. The mineralized intersections (up to 26 m) commonly average less than 1 per cent copper and contain only minor or trace amounts of zinc. A narrow intersection (1.30 m drilled width) in recrystallized chert banded iron-formation assayed 3.5 per cent copper and 910 ppm zinc.

NARNDEE PROSPECTS

Some 65 km southwest of Youanmi townsite is another small, north-striking supracrustal belt again containing mafic and felsic metavolcanic rocks and metasedimentary rocks, intruded by layered mafic to ultramafic rocks. The geology and mineralization appear to be closely similar to the Yuinmery area. Copper-anomalous gossans have been found 2 and 13 km north of Narndee homestead (ca.28°56'S, 118°11'E) and 8 km south-southeast of the homestead. The gossans are stratabound within deformed and metamorphosed felsic volcanic rocks,and associated sedimentary rocks (quartz-mica-chlorite schists) including recrystallized chert (quartzite) and banded iron formation, which collectively form the core of the belt. The most encouraging exploration results were obtained by BHP in 1973-1974 from gossanous quartzite-banded iron-formation in the southern locality which is immediately northwest of Quandong Well. Percussion and rotary drilling yielded best intersections of 8 m drilled width averaging 1.3 per cent copper (including 2 m of 2.65 per cent copper), and 4 m averaging 1.07 per cent copper (including 2 m of 1.85 per cent copper). Most other intersections were less than 0.5 per cent copper on average, and the highest zinc assay was 0.24 per cent over 4 m. Iron sulphides dominate the mineralization. The better copper and zinc values were found in the hinges of folds, indicating some upgrading by mobilization during regional metamorphism.

QUINNS PROSPECTS

Small copper-zinc prospects were discovered by Newmont in 1976 near the Quinns gold mining centre, 1 to 3 km west of Nowthanna Hill (27°03'30"S, 118°33'30"E). The area is near the southeastern margin of a supracrustal belt extending northwards beyond Meekatharra, and consists of metamorphosed and complexly folded fragmental felsic volcanic and associated layered sedimentary rocks (including recrystallized chert and banded iron-formation), structurally overlain by basic volcanic rocks. At the main prospect (about 1.5 km west of Nowthanna Hill), thin (50 cm) gossanous zones in quartz-feldspar-chlorite-muscovite-magnetite schist and quartz-magnetite-chlorite rock (meta-banded iron-formation) are thickened in a complex fold hinge which plunges moderately towards the south-southwest. Pyrite and pyrrhotite dominated mineralization was intersected in drill core but best assays were only 2 to 3 per cent copper and 0.9 per cent zinc over 0.63 m drilled width.

WONGAN HILLS PROSPECT

The Wongan Hills prospect (30°55'19"S, 116°38'25"E) is 6.1 km at 247 degrees from Wongan Hills townsite, at the southern end of the Wongan Hills range which is largely made up of north-striking amphibolite. A north to north-northwest-trending, low, scrub-covered ridge in the centre of a cleared paddock is 350 m long and 25 to 75 m wide. It contains massive hematite gossan (after magnetite), porous largely exotic limonitic gossan (after sulphide), ferruginous, weathered garnet-mica schist and coarsely recrystallized quartzite all of which crop out discontinuously. There is very little exposure besides the ridge, but semi-pelitic schist float can be found. The dominant structure in outcrop is a strong mineral lineation, visible in host rocks and limonitic gossan, which plunges at 20 to 40 degrees towards 320 to 350 degrees. Discernible layering at the northern end of the ridge dips north-north-westerly and westerly, but possible transposition and probable folding complicate interpretation.

The prospect was discovered by Otter in 1975, who have subsequently drilled four inclined diamond drillholes (totalling 787 m) collared west of the northern half of the ridge. This drilling indicated that the surface gossans do not persist at shallow depth below the ridge, but another mineralized zone was intersected which assayed 0.66 per cent copper and 7.5 g/t silver over a drilled width of 9.8 m. Two 1 m portions of this intersection assayed 1.26 per cent and 1.75 per cent copper. The lack of depth persistence could be explained if, as seems likely from surface structure, the mineralized zones are folded and rodded, and plunging to the north-northwest. However, further diamond drilling carried out by Aquitaine suggests that the mineralization plunges steeply towards the south-southeast.

The primary sulphide mineralization (below 120 m depth) consists of chalcopyrite (and magnetite) as veinlets and disseminations (to 20 per cent) plus minor arsenopyrite, cubanite, pyrite (cobaltiferous) and marcasite (Appendix 1). The host rocks resemble those at the Bunnawarra prospect and in the West River area, being garnetiferous quartz-biotite-muscovite-chlorite-magnetite bearing schists, locally containing iron-rich (fayalite, grunerite) and aluminous (sillimanite, andalusite) layers, and tourmaline. Almandine and magnetite seem to be preferentially associated with the sulphides. Individual assemblages may be complex and probably reflect metasomatism. High amphibolite facies regional metamorphism has affected the area.

COPPER-GOLD-SILVER-ZINC DEPOSITS OF THE RAVENSTHORPE-WEST RIVER AREA

INTRODUCTION

Nearly half of the total State production of copper ore and concentrates has come from this area, about 550 km southeast of Perth and 25 to 40 km inland from the south coast (ca. 33°30'S, 120°00'E). Ravensthorpe is close to the southern margin of the Yilgarn Block and to the western boundary of the Eastern Goldfields Province, though this "boundary" is ill-defined in this region.

The mineralization is concentrated in five groups of deposits, the Kundip, Mount Desmond, Mount McMahon, Ravensthorpe and West River groups, which form an arc, convex northwards, around the perimeter of an ovoid syntectonic granitoid diapir (Fig. 42). Most deposits are located in north-northwest to east-northeast-trending shears of fractures within garnetiferous amphibolite, and mafic to felsic metavolcanic rocks showing varying degrees of primary textural preservation and deformation. The only comprehensivė recent account of the geology and mineralization of the region is by Sofoulis (1958b). The Ravensthorpe Sheet was mapped in 1971 (Thom and others, 1977).

Total production of contained copper is 20 115 t, plus nearly 4 000 kg of gold and about 2 580 kg of silver. There have been two major mining periods in the past, and during this decade the area has attracted interest from exploration companies seeking copper and nickel mineralization.

HISTORY

Although the first discovery of gold-copper mineralization was made in 1891 or 1892 north of Mount McMahon, mining proper did not begin until 1899 when finds were made at Ravensthorpe, Mount Benson, Mount Desmond and Kundip (Sofoulis 1958b, p. 19). The area was proclaimed as the Phillips River Goldfield on September 14th, 1900. The major periods of copper ore production were from 1901 to 1918 (about 8 000 t of contained copper), and from 1957 to 1971 (11 564 t of contained copper). Cupreous ore was produced in small amounts from 1950 to 1971 (186 t contained copper). Eleven mines have accounted for 95 per cent of the copper ore production. These are the Desmond, Elverdton, Flag, Harbour View, Hillsborough-Fairplay, Last Chance, Marion Martin, Mount Benson, Mount Cattlin, Mount Desmond and Surprise mines (Table 35, Fig. 43).

At the beginning of the century, the bulk of the ores and concentrates were smelted locally and shipped out of Hopetoun, but during the second production period a treatment plant (capacity 10 000 t of ore per week) was set up at Elverdton to produce copper concentrates and recover the coarse gold. Further details are given in Chapter 1.

In 1952, radioactive minerals were detected at the northern end of the Elverdton workings (Sofoulis, 1958c). This discovery stimulated a diamond drilling programme (120 m spacings) which was carried out by Western Uranium Mines N.L. (subsidiary of Norseman Gold Mines N.L.) in 1954-1955. No important concentrations of radioactive minerals were found, but shear-controlled copper mineralization averaging 1.5 per cent copper and about 30 g/t gold was indicated to extend discontinuously over a 670 m length and an average width of 12 m, at vertical depths between 55 and 350 m. The company, Ravensthorpe Copper Mines N.L. (RCM), was formed to commence working the Elverdton-Mount Desmond deposit in 1957, and subsequently reopened the Mount Cattlin, Marion Martin, and Gem Consolidated (Beryl) mines. Lack of profitability and declining copper prices caused operations to cease in March, 1971. By this time the bulk of the proved reserves had been extracted from the mines (to a depth of 150-200 m at Elverdton-Desmond). The company was restructured as Hollandia-Ravensthorpe N.L. in 1973, and feasibility of extracting copper at Elverdton-Desmond by *in situ* leaching was studied, but with negative results.

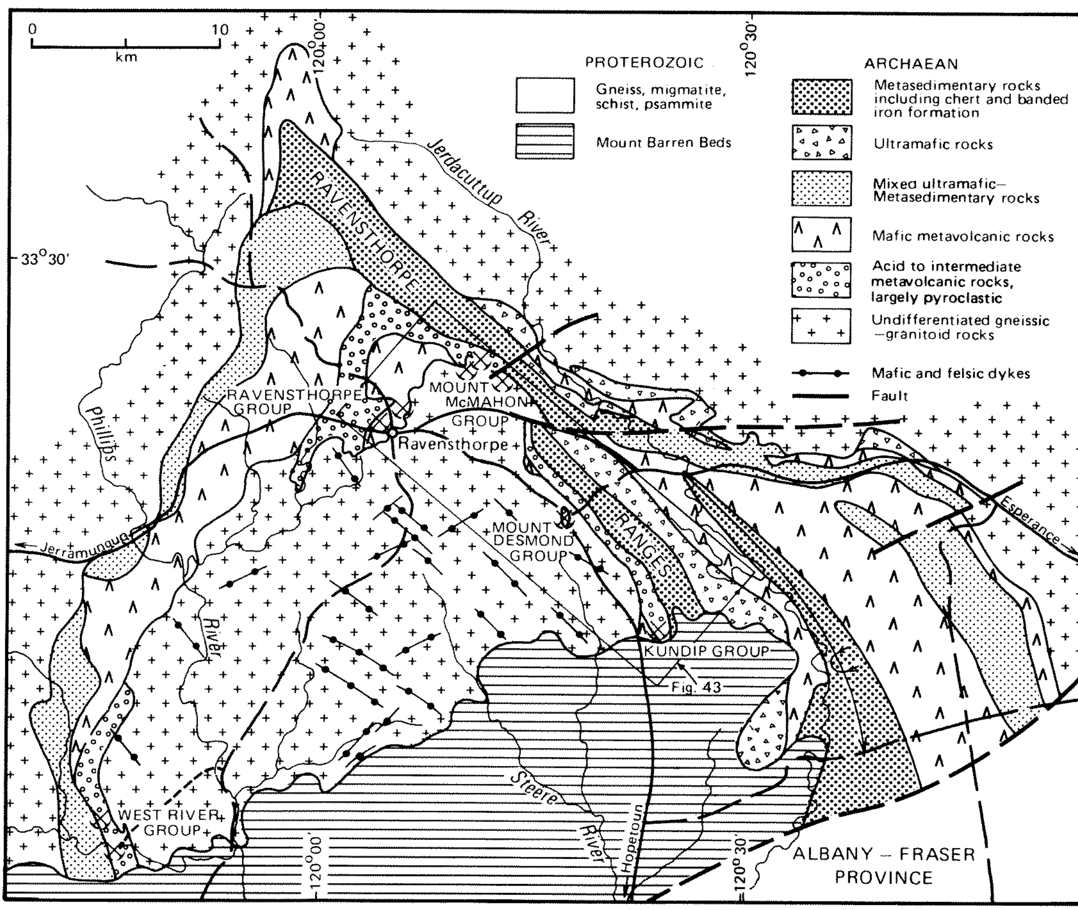

Figure 42. Interpretative outline geological map of the Ravensthorpe-West River area

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In the 1970's exploration in the Ravensthorpe-West River area has involved several companies including Norseman Gold Mines, Carr Boyd, PMI, Unimin, CRA, Amax, WMC, and Amoco. In joint venture with Hollandia, Unimin has investigated the major productive centres and carried out some successful diamond drilling in the Gem Restored—Harbour View—Flag area at Kundip. Here, apparently stratabound disseminated pyrite-chalcopyrite mineralization was encountered in acid to intermediate and basic metavolcanic rocks including pyroclastic varieties. This discovery, a reassessment of surface and sub-surface geological data in the Ravensthorpe-Kundip area, and observations at West River imply that the overall metallogenesis might involve originally stratabound volcanogenic mineralization variably remobilized, during deformation, regional metamorphism and granitoid emplacement, into structural sites.

REGIONAL GEOLOGY

An ovoid, domal pluton of biotite and/or hornblende granodiorite to tonalite forms the major, and centrally located feature of the area (Fig. 42). The southern part of the pluton is concealed by south-dipping quartzite, dolomite, phyllite and conglomerate of the Middle Proterozoic Mount Barren Beds. Farther south, Proterozoic and Archaean rocks become involved in the Albany-Fraser Province (a mobile belt).

Archaean supracrustal rocks form narrow, steeply dipping belts on the western and eastern sides of the pluton; these belts merge northwards. Supracrustal rocks are dynamically or statically recrystallized in the greenschist and amphibolite facies of regional metamorphism. Many dynamically recrystallized rocks have garnet porphyroblasts or amphibole rosettes superimposed on the foliation. East of Ravensthorpe, the eastern belt widens southwards, and here Thom and others (1977) recognized a major, southeasterly plunging overturned syncline, which has an axial surface dipping steeply to the southwest. Sofoulis (1958b) also placed a synclinal axis here, but considered this to be a subordinate structure to a postulated syncline in the metasediments of the Ravensthorpe Range. This syncline is not substantiated by facing data (Thom and others, 1977). The Kundip and Mount Desmond mine groups occur in the western overturned limb of the syncline of Thom and others, (1977), which dips steeply southwestwards. The Mount McMahon and Ravensthorpe mine groups may be in equivalent positions farther north, but the intrusion of granitoids has broken up and narrowed the belt, making interpretation difficult.

Proceeding outwards from the pluton, the sequence in the western limb begins with fine-grained to coarse-grained, garnetiferous hornblende-plagioclase amphibolite (mafic metavolcanics), which is most extensive north of Ravensthorpe and is the host rock at Marion Martin mine and Mount Cattlin mine (in part). This unit is succeeded by acid to intermediate metavolcanic rocks including recognizable, though deformed, agglomerate and tuff (e.g. Kundip). Where strongly deformed and recrystallized (e.g. West River), quartz-biotite-calcium/magnesium and magnesium amphibole-feldspar-garnet bearing rocks are found. Mafic meta-igneous and metasedimentary horizons are interspersed in the unit. Fine-grained to coarse-grained clastic metasedimentary rocks, chert and banded iron-formation follow and form the Ravensthorpe Ranges, although northwest of Ravensthorpe there are extensive areas of metabasalt and garnetiferous amphibolite apparently structurally above the intermediate metavolcanic unit. Overlying the metasedimentary BIF unit of the Ravensthorpe Range are serpentinized extrusive and intrusive komatiitic peridotites, followed by pillowed tholeiitic metabasalt, and finally by tightly folded metamorphosed siltstone, carbonaceous shale and tuffaceous shale in the core of the syncline.

The granodiorite-tonalite pluton, and to a lesser extent the enveloping supracrustal rocks are cut by east-northeast and northwest trending metamorphosed dolerite-gabbro and felsic porphyry dykes, and rare comparatively unmetamorphosed, east-west oriented (Proterozoic) dolerite dykes.

MINERALIZATION

The main economic mineral associations are as follows:

(1) chalcopyrite-gold-pyrite-pyrrhotite-magnetite-ilmenite-quartz;

(2) quartz-gold-secondary copper minerals; and

(3) chalcopyrite-sphalerite-pyrite-pyrrhotite-quartz.

The first association is commonest, and all associations contain silver. Accessory amounts of cobalt minerals such as cobaltite (Simpson, 1951 p. 63) and bravoite (Appendix 1) have been recorded. The quartz-gold association predominates in the oxidized zone, which occurs to depths of 6 to 60 m, and passes downwards into less auriferous iron-copper sulphides in many of the mines. The zinc-bearing third association is only known from the West River group, although sphalerite inclusions have been observed in chalcopyrite from Mount Benson and Elverdton-Mount Desmond mines. With a few minor exceptions the mineralization is restricted to within 1 to 2 km of the pluton's periphery, and occurs in the structurally lowest amphibolite and the adjacent acid to intermediate metavolcanic unit. The mineralization is largely confined by parallel or *en echelon* shears which are up to 200 m long and 30 m wide (exceptionally 700 m long at Elverdton-Mount Desmond), and strike north-northeast to east-northeast. The ore shoots are commonly of the order of 60 m long and 2 m wide, and were rarely mined below about 60 m vertical depth in the first main production period (1901-1918), partly because of decreasing gold assays. Supergene enrichment of gold has probably taken place.

TABLE 35. MINE PRODUCTION OF COPPER ORE AND CONCENTRATES FROM THE RAVENSTHORPE—WEST RIVER AREA

Mine	Main metal(s)	Copper ore and concentrates (t)	Average grade (%)	Gold (g/t)	Silver (g/t)	Contained copper (t)
		KUNDIP GROUP				
Alice Mary	Au	33.59	12.09	[1](151.48)	[1](156.22)	4.06
Ard Patrick	Cu	2.53		8.46		0.27
Australia	Cu	22.86	19.02			4.35
Christmas Gift	Au-Cu	200.21	10.64			21.31
Flag	Au-Cu-Ag	15 544.33	1.63	19.04	(2.37)	253.23
Gem	Au	4 318.34	0.53	24.25		22.76
Gem Consolidated (Beryl)	Au	[2]6 514.67	1.20	27.10		77.98
Harbour View	Au-Cu-Ag	12 423.44	2.10	16.11	0.68	264.42
Hecla	Cu	25.34	11.88			3.01
Hillsborough-Fairplay	Au-Cu	836.14	4.36			191.98
Little Wonder	*Cu-Au*	17.22	9.07			1.56
Lone Star	Cu-Au	13.13	8.53			1.12
May Day	Au	6.98	5.16			0.36
Mosaic	Cu-Au-Ag	73.41	11.09			8.14
Mount Pleasant	Cu	29.32	12.32			3.61
Mount Stennet	Cu-Au	303.77	13.92	(18.11)		42.29
South Gift	Au-Cu					0.40
Two Boys	Au	11 463.79	0.25	22.65		28.75
Sundry Claims	Cu	161.52				26.97
Sub totals		51 990.59	1.83			956.57
		MOUNT DESMOND GROUP				
British Flag	Cu-Au	47.43	18.49	9.57		8.77
Comstock	Cu	66.70	18.67	(4.86)	29.00	12.44
Desmond	Cu-Au-Ag	[2]2 683.44	14.51	4.36		286.08
Desmond Central	Cu	7.38	18.29			1.35
Elverdton	Cu-Au-Ag	96 869.80	15.34	(11.84)	(38.66)	14 850.03
Elverdton South	Cu	[2]53.76	16.26	(1.83)		8.74
Elverdton Welcome Stranger	Cu	5.39	16.01			0.86
Great Oversight	Cu	109.56	10.96	(1.28)		12.01
Ironclad	Cu-Au-Ag	379.89	17.13	8.66	11.00	65.05
Mount Desmond	Cu-Au-Ag	[2]1 992.56	12.62			251.58
Mount Garrity	Cu	49.49	19.80			9.81
PLP	Cu-Au	[2]229.85	15.72	2.28	1.09	36.14
Resurrection	Cu-Au	1.12	9.09	1.72		0.10
Rio Tinto	*Cu-Au*	*6.60*	*18.00*	*1.51*		1.19
Thistle and Shamrock	Cu-Au-Ag	141.21	15.76	(2.92)	1.61	22.24
Sundry Claims		142.50	17.80			26.18
Sub totals		102 786.68	15.17			15 592.57
		MOUNT McMAHON GROUP				
Ballarat-Emily Hale	Cu-Au	347.16	13.03	(0.57)		45.26
Birthday	Cu-Au	18.40	12.23	(9.30)		2.25
Commonwealth	Au-Cu	45.05	11.12	(3.52)		5.01
Last Chance	Cu-Au-Ag	1 451.71	15.63	(0.33)	(1.31)	226.83
Last Chance North Extend.	Cu	2.59	13.33			0.35
Last Chance Proprietary	Cu-Au	277.32	11.72			32.51
Mount Benson	Cu-Au-Ag	2 220.34	8.36	(13.35)	(6.88)	185.65
Mount Benson East (Mary)	Cu	936.12	13.63	0.83	(1.33)	127.62
Mount Benson Extended	Cu-Au-Ag	105.53	15.79	(7.42)	(2.56)	16.67
Sub totals		5 404.22	11.88			642.15
		RAVENSTHORPE GROUP				
Copper Horseshoe	Cu	15.22	13.53			2.06
Floater	Au	[2]49.48	1.02	65.21		0.51
Grafter	Au	69.45	2.91	6.46		2.02
Grimsby	Cu-Au-Ag	16.10	15.72			2.53
Kuracca	Cu-Au-Ag	3.40	8.66	16.19	29.73	0.29
Maori Queen	Au	13.95	1.31	23.92		0.18
Marion Martin	Cu-Au-Ag	[2]6 087.83	12.71	(2.63)	(1.83)	773.55
Mount Cattlin	Cu-Au-Ag	[2]25 161.73	5.26	(7.26)	(5.69)	1 323.60
Mount Cattlin South	Cu	4.28	5.94			0.25
Mount Cattlin West	Cu	233.63	16.55	(3.05)	(2.88)	38.68
Sunset	Cu	562.59	11.78			66.26
Surprise	Cu	1 378.44	15.89	(1.13)		219.15
Sundry Claims	Cu	1 189.95	11.61			138.12
Sub totals		34 786.05	7.38			2 567.20
		OTHER AREAS				
Sundry Claims	Cu	1 684.31	8.14			137.05
Copper King[2 3]	Cu					
Last Venture[2]	Cu	36.14	14.69			5.31
West River centre[2]						
Sundry Claims	*Cu*	*161.71*	17.60			28.46
Sub totals		1 882.16	9.07			170.82
Totals		196 849.70	10.11			19 929.31

[1]. Figures in parentheses represent gold and silver contents of only part of the stated tonnages of copper ore.
[2]. Production for the period 1958-1971 was included without discrimination with Elverdton mine.
[3]. Production not recorded, some may be included in sundry claims

In the first production period, head grades of copper ore averaged 8.7 per cent copper and 25 g/t gold, with great individual variation in tenor (Table 35). The gold contents were commonly critical in determining profitability, but at best were rarely in excess of 95 g/t (Sofoulis, 1958b, p. 125). The general run of the best ore assayed 31 to 47 g/t gold, but the major copper ore producing mine at Elverdton averaged only 2.37 g/t gold.

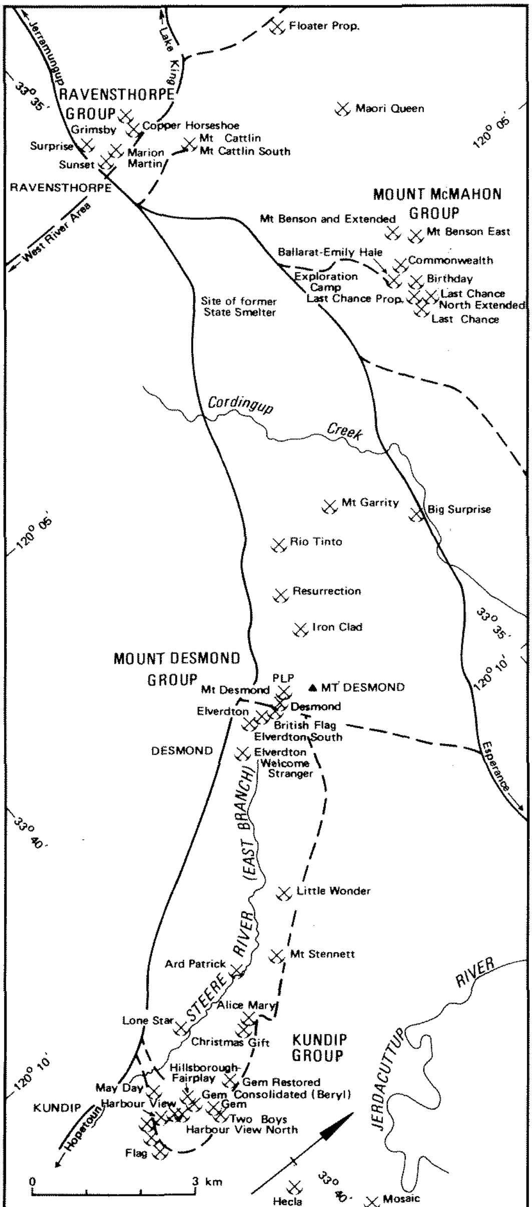

Figure 43. Principal mines in the Ravensthorpe, Mount McMahon, Mount Desmond and Kundip groups

In the second production period (1957-1971) the aggregate head grades of copper ore from Elverdton-Mount Desmond, Gem Consolidated (Beryl), Marion Martin and Mount Cattlin were in the range of 1.41 to 2.40 per cent copper but averaged only 1.52 per cent copper 0.81 g/t gold and 2.64 g/t silver.

In detail, the modes of occurrence and textures of mineralization (see also Appendix 1) are as follows:

(i) sulphide veins, veinlets and stringers with or without hydrothermal quartz occurring parallel to or transecting the host rock foliation;

(ii) breccia ore consisting of country rock fragments enclosed by foliated sulphides; and

(iii) foliated disseminated sulphides, apparently conformable with the host rock layering and foliation.

The first two types represent mineralization in structural sites, and are the commonest. Some layer-parallel veins (e.g. West River) may represent recrystallized and slightly mobilized, originally stratiform volcanogenic mineralization. The third type appears to be present at least in the Kundip area, and may also be volcanogenic in nature. Though some ore may be foliated, randomly oriented (i.e. "static") metamorphic intergrowths between silicates (e.g. amphibole) and sulphides are typical (see Appendix 1). Like the garnet porphyroblasts commonly superimposed on the foliation of amphibolites, this texture would appear to result from later metamorphism unaccompanied by deformation. This metamorphism evidently followed the earlier ("dynamic") recrystallization responsible for the development of foliation.

Little is known about mineral zonation in ore shoots, but chalcopyrite would behave differently to pyrite during deformation and regional metamorphism because of its lower strength. Chalcopyrite-rich margins have been observed in some drill intersections of sulphides. Higher grade, more massive shoots within disseminated mineralization have been reported from Elverdton and Mount Desmond mines. Garnet-, amphibole-, biotite-or magnetite-rich wall rocks seem to be preferentially associated with mineralization in several cases (e.g. Mount Benson, Mount Cattlin, West River), though magnetite seems to decrease in abundance southeastwards from Ravensthorpe to Kundip. These phenomena may be the product of sulphide-silicate reactions (e.g. loss of sulphur, movement of silicon, aluminium, sodium, potassium, calcium, iron) during metamorphism (cf. Plimer, 1976), though the presence of mineralization at or near lithological contacts (e.g. West River, Mount Cattlin) means that silicate-silicate reactions could also be partly responsible.

GENESIS

Sofoulis (1958b, p. 98-100) regarded the ore bodies as hydrothermally emplaced metasomatic replacements, localized in shears generated during the emplacement of the central granodiorite-tonalite pluton, but he considered that the ultimate source was mafic volcanic rock previously melted and assimilated by the pluton. There is little information on which to base a meaningful hypothesis of ore genesis. The recognition of the perhaps previously understated importance of acid to intermediate pyroclastic metavolcanic rocks as hosts to mineralization, is significant in hinting at the presence of variously remobilized, originally stratiform volcanogenic sulphides. Stratabound pyritic sulphide horizons up to 1 km long and 30 m thick are known from the Kundip and Ravensthorpe areas. Most pyrite from the copper mines is cobalt-rich, a feature consistent with a volcanogenic origin (see Appendix 1). The presence of stratabound, though apparently minor, copper-zinc mineralization in such rocks at West River is also important in this regard, and sphalerite in an accessory mineral in some Ravensthorpe area mines. The mineralization and host rocks have evidently suffered a complex history of deformation, metamorphism and metasomatism, which makes genetic reconstruction that much more difficult.

ELVERDTON-MOUNT DESMOND MINE

This mine (33°37′40″S, 120°08′30″E) has exploited the principal mineralized shear zone in the area, which strikes north to north-northwest and dips steeply east (Fig. 44). Diamond drill core on site consists of abundant medium-grained biotite granodiorite, fine-grained plagioclase-hornblende-chlorite-quartz rocks, metadolerite, metabasalt, and quartz-plagioclase-biotite-chlorite-(hornblende) schist some of which exhibits textures of pyroclastic aspect and contains feldspar megacrysts. This rock assemblage would seem to represent a large inclusion or raft of mafic to felsic (largely metavolcanic) supracrustal rocks within the marginal zone of the pluton. The primary ore mineralogy is pyrite-chalcopyrite plus minor pyrrhotite and magnetite, and rare ilmenite in a quartz gangue. A trace of galena has been recorded, and in the oxidized zone (to 26.5 m depth), malachite, azurite and covellite were found, but there was no economically important supergene enrichment of copper. A silver-bismuth telluride mineral is a rare accessory (Appendix 1).

The mineralized zone was 2 to 18 m wide, but the average width mined was 0.75 to 2.75 m wide and consisted of irregular shoots commonly displaced in detail by minor faults. Early reports indicate that workings at Elverdton were on the western side of the country rock inclusion, whereas those at Mount Desmond were on the eastern side. By 1920 levels were established at 39.3, 75.9, 107 and 151.8 m depths, with the maximum drive length of 326 m being on the 75.9 m level. From 1901 to 1920, when the mine closed down 41 235.13 t of copper ore averaging 7.97 per cent copper had been produced.

With the exception of 248.10 t of cupreous ore and concentrates (averaging 9.79 per cent copper), produced from shallow levels in 1951-1953, the mine was not developed again until 1958. Then the main shaft was deepened and new levels were put in at 196.9 and 227 m depths, and an exploratory winze was sunk to 264.3 m. Levels at 75.9, 107 and 196.9 m were driven northward to connect with the 59.4, 91.4 and 181.7 m levels at Mount Desmond mine (Fig. 44). Mine production at Elverdton began in 1960 and all payable ore down to the 196.9 m level was stoped out over a drive length of 305 m, and on the 227 m level a 131 m length of stoping was done. At Mount Desmond all payable ore was stoped out between 29.3 m and 157.6 m levels over a mean drive length of 414 m. Two shoots 44 and 73 m long were stoped on the 181.7 m level. Diamond drilling had indicated a 670 m long discontinuously mineralized zone up to 11.89 m wide, and down to a 350 m vertical depth. A 7.92 m drilled-width intersection at this depth averaged 1.7 per cent copper.

Elverdton-Mount Desmond mine accounted for the bulk of the undiscriminated combined reported production for 1958-1971 which also included Gem Consolidated (Beryl), Marion Martin, Mount Cattlin and some small mines at West River. Some 55 634.67 t of sulphide concentrates were produced from 813 565 t of ore treated. Of these concentrates 52 004.05 t yielded 11 564.37 t of copper, 615.5 kg of gold and 2 010.3 kg of silver for grades of 22.24 per cent copper, 11.84 g/t gold and 38.66 g/t silver. Disregarding losses in the tailings, (a sample taken by King (1966) assayed 0.15 per cent copper), the average calculated head grades for the 813 565 t of ore treated are 1.52 per cent copper, 0.81 g/t gold and 2.64 g/t silver. In addition 283.27 t of cupreous ore averaging 13.35 per cent copper was produced.

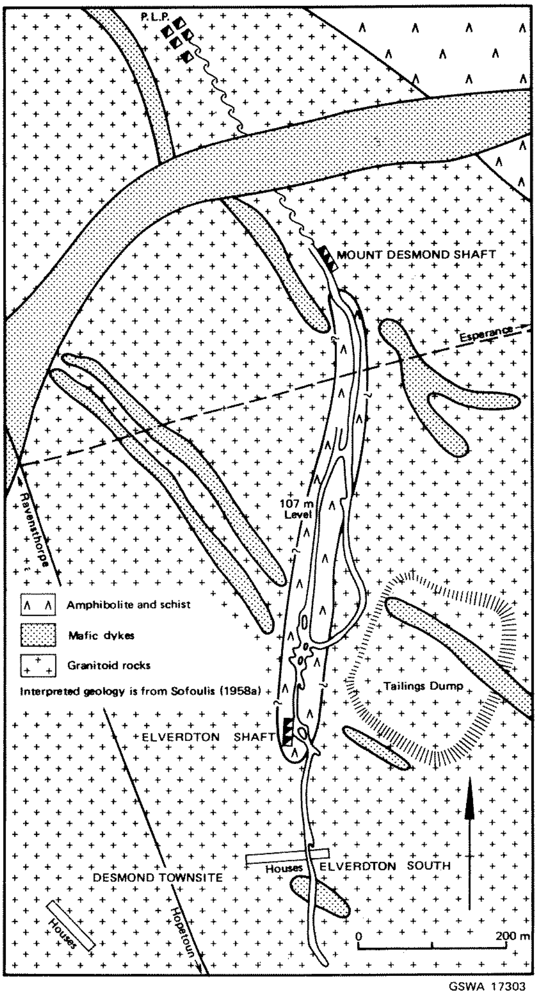

Figure 44. Interpreted surface geology and surface projection of the 107 m level, Elverdton-Desmond mine

In 1960 the Bureau of Mineral Resources (BMR) carried out an airborne magnetic and radiometric survey of the Ravensthorpe area, but the steep, isolated anomalies recorded were associated with granitoid rocks (Wells, 1963). Ground magnetic traverses done by RCM immediately south of Elverdton revealed anomalies, some of which coincided with weak copper mineralization and magnetite (Smith, 1967). In 1965 self-potential, E.M. gun, Turam, induced polarization and magnetic test surveys were run by the BMR at Elverdton (and Marion Martin and Mount Cattlin) in an attempt to locate new ore bodies or extensions to known ore bodies (Smith, 1967). It was recommended that frequency effect induced polarization anomalies obtained in areas adjoining the Elverdton-Mount Desmond mineralized shear to the north and south, be drilled at five localities (target depths 36-91 m, lengths 120-210 m). As far as is known this drilling was not performed.

There is little prospect of economically recoverable mineralization being present in or immediately adjacent to the existing workings at Elverdton-Mount Desmond. The cost of proving any additional mineralization could be prohibitive because of the target depths required (greater than 200 m). The expected low tenors of copper and gold, and a presumed increasing abundance of intrusive granitoid at this depth also offer little inducement. Investigations of the southern and more particularly the northern extensions (approaching and perhaps within supracrustal rocks) of the Elverdton-Mount Desmond shear zone and any possible branches may prove more rewarding.

MAJOR MINES IN THE KUNDIP GROUP

This mine group was primarily gold producing, but the Flag, Gem Consolidated (Beryl), Harbour View, and Hillsborough-Fairplay mines each produced over 100 t of contained copper (Table 35, Fig 43). Only the Gem Consolidated mine was reopened by RCM, but it was closed again in 1962 because the mineralization was of poorer grade than expected.

The country rocks are poorly exposed and consist of variably foliated mafic and acid to intermediate metavolcanic rocks including pyroclastic types which were probably referred to as 'meta-clastic greenstones' by Noldart (1958a, p. 182). The layering and generally sub-parallel foliation in these rocks dips at about 65 degrees to the east-northeast. Diamond drilling carried out in the 1930's in the (a) Hillsborough-Gem and (b) the Harbour View-Flag areas, encountered granitoid rocks in the first area at vertical depths between 76 and 180 m, but drillholes reaching similar depths in the second area bottomed in supracrustal rocks (Noldart, 1958a, Plate 12). The granitoid intrusives may be in a dyke or sill-like body and do not necessarily indicate that the main pluton is at a shallow depth as assumed by Noldart (1958a, p. 181). Porphyry dykes of intermediate composition occur in the Kundip area and are restricted to the acid-intermediate metavolcanics. They strike between east and north and may carry disseminated pyrite and chalcopyrite.

The exploited mineralization is confined to shears commonly striking (i) north-northeast and dipping steeply west (e.g. Harbour View), and (ii) striking east to east-northeast and dipping moderately south (e.g. Flag, Hillsborough, May Day, Gem Consolidated). Some smaller groups of workings are sited on vertical or steeply dipping shears which trend parallel to the strike of the country rocks (e.g. between North Harbour View and Gem Consolidated, and near Gem Restored).

The Harbour View shear is some 600 m long and has been the major copper producing structure in the area. Mining was confined to oxidized material above the water table. The workings were deepest at the southern end where levels were established at 10.7, 22.9 and 42.7 m. Mineralization was found over a 37 m length at the 42.7 m level, and 39.6 m on the 22.9 m level. Water stood at 33.5 m depth in the north and 42.7 m in the south. Smaller amounts of mining were done at the northern end and in the central workings. The width of the mineralized zone varied from a maximum of 4.3 m at the surface to 6.1 m at 42.7 m depth, but the payable ore shoots (largely confined to the footwall) were only 1 to 2 m wide (Noldart, 1958a). Recent diamond drilling by Hollandia-Unimin along the Harbour View shear has intersected disseminated to massive pyrite-pyrrhotite-chalcopyrite mineralization with gold and silver contents over a strike length of 300 m and true widths up to 8 m. Average assays up to 5.47 per cent copper, 16 g/t gold and 16.5 g/t silver have been obtained over significant drill core widths (greater than 1 m).

The Flag mine is the next largest copper producer, and like Harbour View also produced a small amount of silver in addition to the gold for which it was primarily worked. The mineralized zone strikes east and dips 45 to 55 degrees southwards and was stated to be 335 m long, and 0.5 to 3.7 m wide. Separate ore shoots up to 30 m long and plunging west occurred in this zone. The major shoots were stoped from levels established at 15.2, 30.5, 45.7, 61.0 and 91.4 m depths, although most mining was confined to shallower levels in oxidized mineralization above the water table at 31.1 m depth. Mineralization at 91.4 m was described as pyrite and quartz shoots (exposed over a 45.7 m length) with only very minor chalcopyrite. Bornite is present near the water table. Picked copper ore from the oxidized zone averaged 8.8 to 11.0 per cent copper.

The Hillsborough-Fairplay mine produced copper ore from 1906 to 1924 from a steeply south-dipping shear at Fairplay, and a south-east dipping shear at Hillsborough. A total of 63.9 m of drilling was done from levels at 47.2 and 58.8 m at Fairplay, whereas 225.4 m of drilling was done from 36.3 and 50.3 m levels at Hillsborough. Many minor faults cut the ore shoots which probably consisted of quartz-pyrite-chalcopyrite in the primary zone.

TABLE 36. MINE PRODUCTION OF CUPREOUS ORE AND CONCENTRATES FROM THE RAVENSTHORPE—WEST RIVER AREA

Mine	Cupreous ore and concentrates (t)	Average grade (%)	Contained copper (t)
Mount Desmond Group			
Big Surprise	105.50	20.95	22.12
Elverdton	631.46	9.84	62.12
Mount Garrity	45.82	14.58	6.68
Sundry claims	3.86	15.60	0.60
Mount McMahon Group			
MC 38	17.73	12.53	2.22
ML 413 (Last Chance area)	104.14	8.46	8.81
ML 416	38.25	8.63	3.30
Ravensthorpe group			
Marion Martin	66.50	12.29	8.17
Mount Cattlin	270.02	7.19	19.39
New Surprise	294.96	15.22	44.89
Sundry claims	70.11	8.43	5.92
Other areas			
Last Venture	7.11	6.86	0.49
Sundry claims	15.57	10.56	1.64
Totals	1 671.03	11.15	186.35

The Gem Consoldiated (Beryl) mine is at the western end of a group of workings trending east to east-northeast said to include the Gem and Two Boys mines (Noldart, 1958a, p. 190). The shears dip north or south, and occur at the contact between a granitoid intrusive to the north and foliated or massive, porphyritic or amygdaloidal mafic metavolcanics to the south. Here, the older workings were to 76.2 m depth. At the Beryl shaft (300 m to the southwest) a total of 198 m of drilling was done on four levels at 101.2, 110.6, 115.8 and 127.1 m. Noldart (1958a, p. 189) states that the Beryl shaft workings, which exploited ore shoots dipping south at about 22 degrees, were probably a down-dip extension of the mineralized zone in the older workings to the northeast. Quartz-limonite-copper carbonate/oxide mineralization passed downwards into pyrite- and chalcopyrite-bearing material. Massive pyrite with good gold values but low copper content was encountered in the area.

MAJOR MINES IN THE MOUNT McMAHON GROUP

The Last Chance (33°33′20″S, 120°06′00″E), Mount Benson (Kingston) (33°33′10″S, 120°05′00″E) Mount Benson East (Mary) mines (33°33′00″S, 120°05′00″E) fall into this category. These mines produced a total of 540.10 t of contained copper in the period 1900-1914 (Table 35), plus small amounts of gold (28.58 kg) and silver (9.11 kg) produced up to 1919. The Mount Benson mine was the only important gold producer in the group.

The main foliation and layering of the country rocks strikes northwest to north-northwest and generally dips steeply southwest or is vertical. Noldart (1958b) described the rocks as sheared, moderately metamorphosed mafic agglomerate interlayered with amygdaloidal, porphyritic, tuffaceous, fine-grained and medium-grained mafic lavas. This sequence is broken up by abundant granitoid intrusions (most being contiguous with the main pluton) and mafic dykes (quartz dolerite, microdiorite, hornblendite). All the mines are close to granitoid contacts. In the late 1960's PMI carried out 1 322 m of inclined diamond drilling over a 500 m strike length in the Commonwealth-Ballarat area southeast of Mount Benson East (Fig. 43). Inspection of the drill core reveals the following rock types: (i) medium-grained biotite granodiorite, (ii) feldsparphyric quartz-feldspar-biotite rock or schist (probably porphyritic meta-dacite), (iii) feldspar-rich green amphibole rock (meta-intermediate volcanic), (iv) foliated quartz-feldspar-green amphibole rock (meta-dacitic ?tuff), and (v) biotite-rich schist. There are rare developments of garnet and magnetite which tend to be associated with disseminated and thin veiniform pyrite-chalcopyrite-quartz mineralization.

At Last Chance mine, the mineralized shear strikes 290 degrees, dips steeply south and is 0.6 to 2.4 m wide. Levels were established at 18.3 (water table 19.8 m), 30.5 and 39.6 m depths, and most production was from the oxidized zone in and above the 18.3 m level. A chalcopyrite-rich vein 45 cm thick was reported from the 39.6 m level, and traces of nickel and cobalt have been noted. Other mineralization below the water table was disseminated.

The Mount Benson mine exploited steeply dipping mineralized shears (average width 1 m) striking 062 and 280 degrees developed in the eastern and western parts of the workings respectively. The eastern workings supplied the bulk of production, which was gained from levels at 21.6, 31.1, 36.6 and 47.9 m depths. Individual shoots were short and inconsistent and had an apparent west plunge. Shoots on the 47.9 m level were reported to assay 1.7 to 10.07 per cent copper and 1.5 to 11.14 g/t gold over unspecified widths. The primary ore contains blebs and veins of quartz-pyrite-chalcopyrite with associated garnet and magnetite. Apparently sulphides occur well above water level (about 35 m) since Noldart (1958b) reported them at a depth of 10.7 m.

At Mount Benson East (Mary) mine the two garnetiferous mineralized shears dip in excess of 80 degrees to the north or south, and strike at 265 and 275 degrees. The payable mineralized zones were 0.6 to 1.5 m wide, and changed from carrying copper carbonates and oxides to bearing chalcopyrite and covellite below about 7.6 m depth. Development took place at the 7.6 m level and at least down to the water table at 24.1 m but no details are available.

MAJOR MINES IN THE RAVENSTHORPE GROUP

The Mount Cattlin (33°34′10″S, 120°02′30″E), Marion Martin (33°34′50″S, 120°02′00″E) and Surprise mines (33°34′50″S, 120°01′50″E) produced a total of 2 316.30 t of copper contained in copper ores from 1901-1920 (Table 35). Mount Cattlin and Marion Martin were reopened by RCM and worked largely from existing levels from 1960-1963 and 1965-1971 respectively for a production of about 64 000 t of ore and concentrates of unknown tenor. In addition small tonnages of cupreous ore were produced from these two mines (Table 36).

The mines are in or very close to the main granitoid pluton in amphibolite, quartz-feldspar-biotite-green amphibole schist, and foliated felsic and intermediate metavolcanic rocks which strike east-northeast and dip steeply north. Amphibolite and biotite-chlorite-green amphibole-quartz schist containing lensoid and porphyroblastic almandine garnets appear to be preferentially associated with the copper-gold-silver mineralization, as observed by Sofoulis (1958b, p. 149). The geological setting is similar to that described for the Mount McMahon group, but the mineralized zones seem to be more or less parallel to the layer-parallel foliation.

The Mount Cattlin mine is developed in a shear zone striking 065 degrees and dipping at about 85 degrees to the north, and known to be mineralized to a depth of at least 200 m and for a 300 m strike length. This zone and the garnetiferous host rocks are cut by (i) a north-northwest striking granodiorite dyke which passes immediately west of the main shaft, and (ii) by two younger, northwest-trending metadolerite dykes further east. These dilational dykes and a west-trending fault divide the ore body into five sections (erroneously referred to as shoots) which have been called A, B, C, D and E "shoots" (Fig. 45). As the dykes dip steeply west, the ore body sections have steep westerly plunges. In the earlier mining period five levels were established at 30.5, 61.7, 91.4, 122.1 and 160.5 m depths, but only D shoot was stoped to the surface from the lowest level. Heavy inflow of salty ground water (545 kilolitres/day) from a fissure between the 91.4 and 122.1 m levels deterred development below the 160.5 m level. In the later mining period a sixth level was added at 192.0 m depth but mining was confined to the older levels, in particular involving the complete stoping out of C and D shoots, and the extraction of the new E shoot found west of the fault (Fig. 45).

The ore body is reported to have averaged 1.5 to 3.0 m in thickness, rarely reaching 4.5 m. Primary sulphides occur below 16.5 m, there being no important supergene enrichment. The typical sulphide ore is massive pyrrhotite-pyrite-chalcopyrite breccia ore containing fragments of green amphibole, chlorite and biotite-rich rock, which may be intergrown with the sulphides indicating a late, static metamorphic recrystallization. The amount of quartz gangue present is very variable. The average grade of the 25 162 t of copper ore mined from 1902-1920 was 5.26 per cent copper. Average gold contents are reported to have been 7.8 g/t above 61.0 m depth and 6.2 g/t to 160 m depth. An inclined diamond drillhole (DDCS1) collared 120 m northwest of the main shaft by RCM intersected a drilled width of 1.37 m assaying 7.5 per cent copper just above the 192 m level (Fig. 45). The C, D, and E shoots probably all continue at depth.

The Marion Martin mine occurs in a foliated zone of garnetiferous amphibolite striking 080 to 060 degrees and dipping vertically to 75 degrees northwards. The mineralization has been exploited to a depth of 95 m over a strike length of 170 m, with the older workings being west of the main shaft whereas the newer workings were to the east. A sub-parallel, 150 m long line of small workings occurs 300 m north of the main mine, in which a 30 m deep level was driven and short shoots were worked over about 100 m of strike. The main mineralized zone is cut by four north-northwest trending metadolerite dykes and numerous tongues of biotite-hornblende granodiorite. Three levels at 38.1, 64.0 and 94.5 m depths were developed from the main shaft, and about 430 m of driving has been done. The oxidized zone is very shallow and most ore was massive pyrite-chalcopyrite (-tetrahedrite) commonly accompanied by disseminated to massive magnetite. Exploratory diamond drilling (ten drillholes) carried out by RCM was targeted on ground magnetic anomalies, which proved to be associated with sulphide mineralization in several places. The average tenor of 6 088 t of copper ore mined from 1901-1920 was 12.71 per cent copper.

The Surprise mine is 350 m west-southwest of the Marion Martin mine shaft, and occurs in a shear striking 080 degrees and dipping vertically to 75 degrees northwards. A line of shafts, originally up to about 25 m deep, extended over 170 m in amphibolite veined by granodiorite and metadolerite. A winze sunk below the main shaft cut a 2.4 m-wide zone of disseminated pyrite and chalcopyrite at a depth of 38 m. The mine was worked from 1901 to 1909 and from 1913 to 1920 and yielded 1 378 t of ore averaging 15.89 per cent copper. Two diamond drillholes, each about 300 m long were sunk into the shear in 1956 by WMC. Little or no mineralization was intersected.

WEST RIVER GROUP

Two small mines and numerous prospecting pits and shafts occur in a north-northwest-striking area 3 km long and 1 km wide, where the West River cuts across the strike. Production has been negligible compared with the Ravensthorpe area, but the mineralization has not been adequately described before, and it is of interest as an example of stratabound copper-zinc mineralization in the area.

Metadolerites, gabbros and basalts, variably foliated and in some areas clearly amphibolitic, are intruded by biotite granodiorite and succeeded westwards by a heterogeneous sequence of mafic to felsic metavolcanic rocks. Feldsparphyric metadolerite and foliated agglomerates to tuffs are clearly recognizable, and are interlayered with feldspar—pale magnesian amphibole schist, feldspathic amphibolite, quartz-mica schist and rosetted quartz-biotite-chlorite-anthophyllite (-garnet-cordierite) rock.

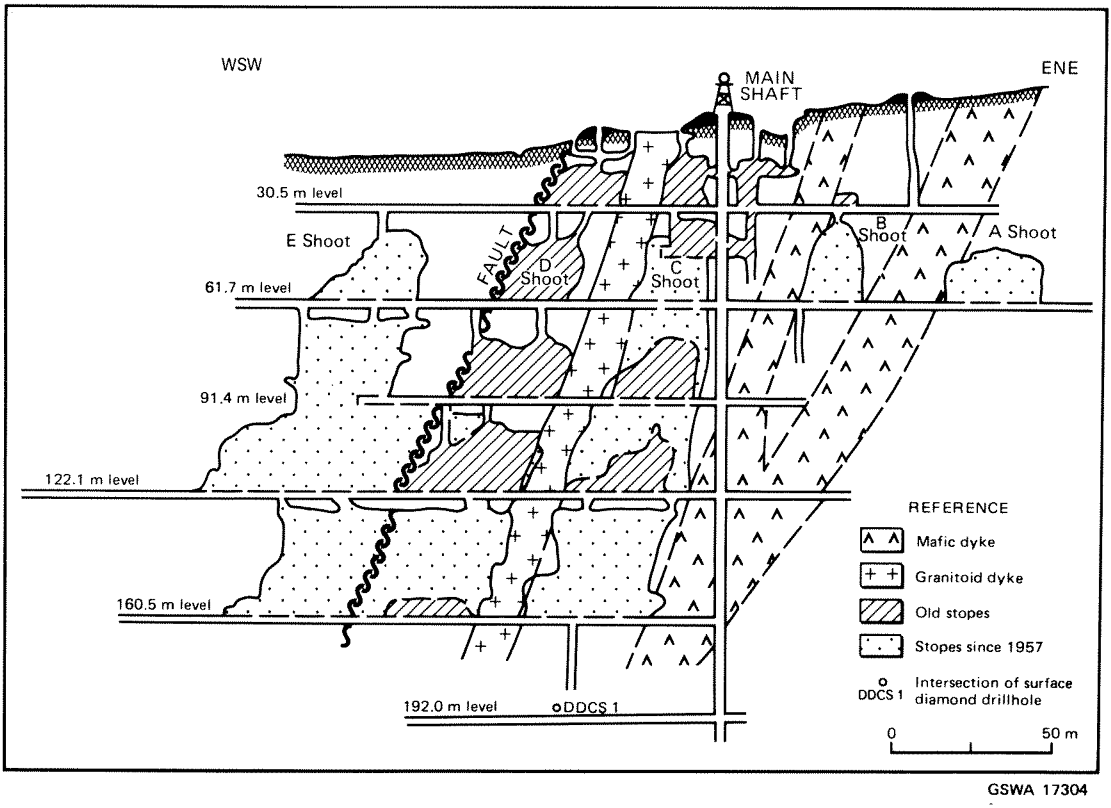

Figure 45. Generalized longitudinal section of the Mount Cattlin mine

Copper shows occur within felsic rocks, at mafic-felsic rock contacts, in quartz-mica-schist or in the rosetted quartz-mica-amphibole rock. Vein quartz may or may not accompany the mineralization which commonly parallels the foliation, which is in turn sub-parallel to the steeply dipping to vertical layering.

The Last Venture mine (33°47′20″S, 119°52′40″E) occurs just south of West River. It was opened up in 1908-1909 when 36 t of copper ore was produced, and again in 1962-1963 when 7 t of cupreous ore were extracted. The mineralized zone strikes 334 degrees and is vertical or steeply east-dipping. The host rock is a rosetted cordierite-anthophyllite-almandine-quartz-biotite-chlorite rock in which a distinct foliation is overprinted by statically recrystallized acicular, radiating anthophyllite. Pyrite and chalcopyrite occur in quartz lenses and veinlets, which may be enveloped by garnet. Thin zones of massive sphalerite may occur too. Sulphide-amphibole intergrowths are also present. Some minor underground development work, including seven diamond drillholes, plus surface diamond drilling (three holes) was carried out by Carr Boyd-NGM in the early 1970's. This work defined a mineralized zone 45 m long and 15 m wide at the 30 m level; the best drill core intersection obtained was 8.7 m assaying 3.43 per cent copper. In 1975 CRA-Carr Boyd-NGM drilled a further diamond hole which intersected two narrow mineralized zones, the best of which assayed 2.43 per cent copper, 6.68 per cent zinc and 31.7 ppm silver over a true width of 1.63 m.

The Copper King mine (33°46′20″S, 119°52′30″E) is 1.5 km north-northwest of Last Venture and was opened at the beginning of the century. The mineralized zone strikes 317 degrees and is at an amphibolite-foliated metadacite contact in the north, but is off contact southwards. The actual host is a quartz-feldspar-biotite schist, partly replaced by fine-grained to medium-grained, recrystallized quartz, and invaded by quartz veins. Sphalerite occurs as aggregates in the veins, and pyrite-chalcopyrite are found as disseminations and strings in the granular quartz. This mine was also re-opened for exploration by Carr Boyd-NGM, and four underground diamond drillholes were bored from a level at 39 m depth (water table 16.5 m). Two parallel mineralized quartz veins 5 m apart were found, but they contained very variable amounts of sulphide. Channel samples across the two 1.3 m wide mineralized zones assayed 0.73 per cent copper and 3.05 per cent zinc, and 2.8 per cent copper and 0.42 per cent zinc.

OTHER MINES

None of the remaining mines has produced in excess of 100 t of contained copper. Available details are to be found in Sofoulis (1958b) and Low (1963) but the data are largely reprinted from Sofoulis, and earlier publications. The style of mineralization is similar to that already described.

CUPRIFEROUS QUARTZ VEINS AND SHEARS (TYPE C)

MAFIC-ULTRAMAFIC IGNEOUS HOST ROCKS

ABBOTTS COPPER PROSPECT

In 1964-1965, a total of 18.16 t of cupreous ore was produced from PA 3587 (26°17′20″S, 118°23′10″E), which is about 5 km north of the Abbotts gold mining centre. The country rocks are reported to be north-striking, siliceous metasedimentary rocks but meta-igneous rocks also occur in the area. The prospect has not been inspected.

GABANINTHA DISTRICT

The mines and prospects in this district, which has been the major copper producing area in the Murchison Province (Table 32), form two distinct groups (Fig. 46). The Mountain View group (26°55′00″S, 118°38′30″E) is immediately north of the abandoned Gabanintha townsite and consists of gold mines which produced ancillary amounts of copper and cupreous ore. The Tumblegum workings (26°55′50″S, 118°38′50″E) are about 1 km south of the townsite, and, though initially gold producing, have since yielded nearly 5 000 t of cupreous ore. The Lady Alma workings (26°57′50″S, 118°40′50″E) are 5 km southeast of the townsite and were mainly for copper. This area has also been informally called "Copper Hills", and small prospects occur 2 km south of the main Lady Alma group, to the south of Copper Hills Well (Fig. 46).

The country rocks strike north-northwest, and dip steeply east or west. They consist of (i) metamorphosed tholeiitic basalt, dolerite and gabbro, pyroxenite, peridotite and dunite (all with relict textures); (ii) amphibole-chlorite rock, talc-chlorite-carbonate schist and foliated versions of the mafic rocks; and (iii) biotite-hornblende granitoid rocks which intrude the supracrustal rocks in the east. Meta-dacitic and ultramafic tuffs are a conspicuous element at the Mountain View group and Tumblegum. Cupriferous limonite-quartz occupies shears in this sequence.

The Mountain View group consists of (a) a north-northwest trending line of shallow gold workings (shafts and stopes) exploiting 1 to 2 m wide subvertical quartz veins, and (b) deeper gold-copper workings grouped around the old treatment plant. In the period 1906 to 1919, 311 t of copper ore averaging 24.27 per cent copper were produced, and from 1953 to 1966, 70 t of cupreous ore assaying 8.83 per cent copper were extracted. Development in the deep workings was by levels at 15.2, 33.5, 48.8 and 61.0 to 64.0 m depths over strike lengths up to 40 m. The water table stands at 22 m. Iron-copper sulphides were encountered in the deeper levels and were presumably worked for gold, the copper being mined from the oxidized zone. An inclined diamond drillhole put in by Union Oil-Hanna-Homestake in 1970 did not encounter mineralization.

The Tumblegum workings occur on a vertical or steeply east-dipping shear striking 013 degrees and opened up discontinuously for 400 m. The cupriferous limonite-quartz vein is 0.9 to 1.5 m wide. The workings at the southern end of the shear were to 91 m depth (water at 18.3 m) over a 100 m length, and reached 40 m depth in the north over a 61 m length. From 1955 to 1962 the tailings were treated and 4 967 t of cupreous ore averaging 3.09 per cent copper extracted. Two diamond drillholes bored in 1966 and 1970 failed to find mineralization.

The Lady Alma group produced copper and cupreous ore containing 117 t of copper in 1906, 1909 and 1954 to 1960. Some 40 t of the cupreous ore came from prospects 2 km to the south of the main group, in the area south of Copper Hills Well (Fig. 46). The Lady Alma mine is 450 m southwest of the old smelter site, and is located in a north-northwest-trending shear on or near a contact between fine-grained to medium-grained serpentinite and tholeiitic meta-gabbro, metadolerite and metabasalt. The mine (now collapsed) was 36.6 m deep (water at 29.0 m) and developed over a 46 m strike length. The ore shoots were thin and short, but contained rich pockets of chalcocite with some quartz and chalcopyrite. The Copper King mine is 145 m to the south-southwest of Lady Alma, and was mined to 27.4 m depth and developed in east-west and north-south directions but little mineable ore was found. Massive, copper-stained limonite gossans and quartz-malachite-azurite-chrysocolla veins are present at the surface. Diamond drilling by Union Oil-Hanna-Homestake in 1970 indicated limited continuity of low-grade (1 to 4 per cent copper) mineralization over 0.24 to 2.2 m widths to the north and south of Lady Alma, and medium-grade (5 to 7 per cent copper) mineralization over widths of 0.58 to 1.16 m at Copper King. The primary sulphides are associated with massive magnetite.

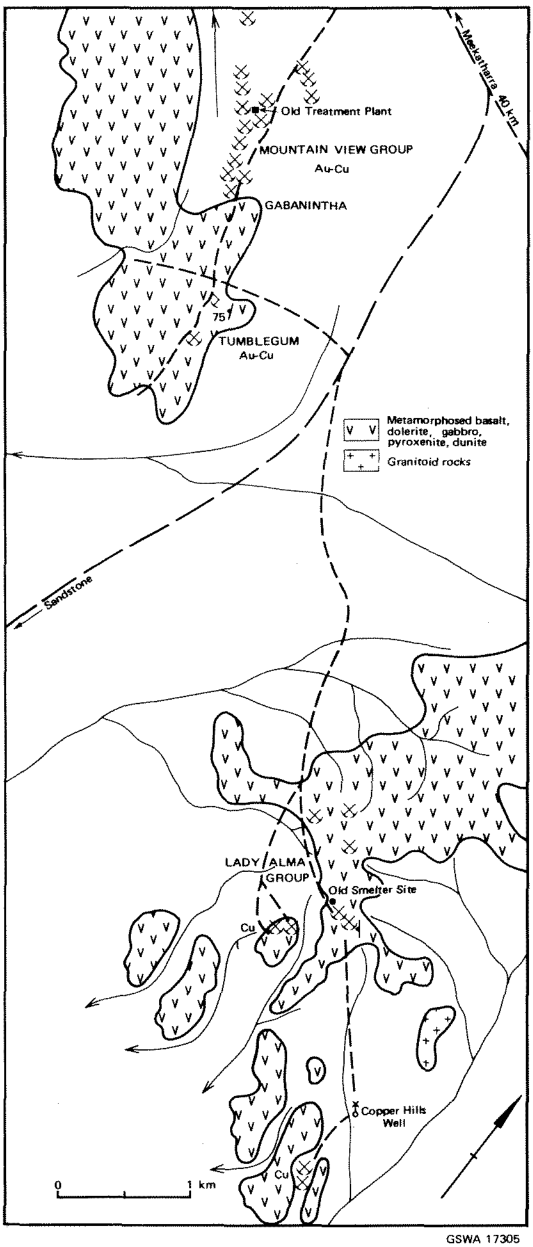

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Figure 46. Copper mines and prospects in the Gabanintha district

Prospecting shafts (deepest 17.5 m) and pits are also present near the old smelter site, close to a north-west-striking contact between talc-chlorite-carbonate bearing schist to the east and metagabbro to the west. Five inclined diamond drillholes collared in the metagabbro failed to find mineralization, except for 4.66 m drilled width assaying 2.45 per cent copper in the central hole which could not be matched along the strike in the other holes.

In the area near Copper Hills Well, north-north-west-striking shears subparallel to, and at or near a metagabbro (east) and talc schist contact contain cupriferous limonite-quartz. Six inclined diamond drillholes (Union Oil-Hanna-Homestake) collared in the metagabbro, intersected several narrow widths (0.40 to 3.50 m) of low-grade (1 to 3 per cent copper) iron-copper sulphides. These probably correspond to discontinuous mineralization present over a strike length of some 500 m.

The steep attitude and thin, discontinuous nature of the mineralization in the Gabanintha district makes it of poor economic significance.

DAY DAWN GOLD MINING CENTRE

Small tonnages of copper and cupreous ore containing 13.04 t of copper were produced here (27°26′30″S,117°51′30″E) in the periods 1900 to 1914 and 1954 to 1956. Cupriferous quartz veins strike northwest to north-northwest in metabasaltic country rocks. Most ore exploited was probably copper carbonate and chalcocite bearing material. Further details are given by Low (1963, p. 129-131).

KATHLEEN VALLEY GROUP

This mine group (ca.27°30′S, 120°33′E) produced copper and cupreous ores containing a total of 266 t of copper in the period 1908, 1945 and 1951 to 1965 (Table 32). This bulk of this production came from workings which are up to 1 km west of the abandoned Kathleen Valley townsite, and subordinate amounts of cupreous ore were from the Mount Mann area 3.5 to 4.5 km north of the townsite. The mineralization consists of thin (less than 1 m), short, pyrite-chalcopyrite-quartz veins occupying west to north-northwest trending fractures and faults. The country rocks comprise a metamorphosed layered gabbro—anorthositic gabbro complex and associated tholeiitic basalt, which generally dip steeply to the northwest. Practically all mining has been in copper carbonate, oxide and supergene sulphides in the oxidized zone above the water table (about 30 m depth). Average grades obtained from mined ore were 11 to 12.5 per cent copper.

At Kathleen Valley townsite the main workings are *Shepherd-Copper King* (27°30′40″S, 120°33′30″E). The former was the major producing mine and small amounts of silver (27.7 kg) and gold (0.40 kg) were contained in copper ore produced in 1956 to 1957. The workings near Mount Mann (27°28′00″S, 120°33′10″E) were opened up in 1957 and consist of shallow open cuts and gouges on the hill summit and 1 km to the north-northeast, and a shallow shaft and drive in an alluvial flat 800 m southwest of the summit.

The mineralization appears to be of little economic significance.

MOUNT SIR SAMUEL GROUP

This was primarily a gold mining area consisting of auriferous quartz-pyrite (-chalcopyrite) veins emplaced in north-trending fractures in steeply dipping tholeiitic metabasalt. Where enriched in the oxidized zone, the veins were worked intermittently from 1942 to 1966 at two localities for copper and cupreous ore totalling 17.27 t of contained copper. The southern locality is 1 km northeast of the townsite (27°38′00″S, 120°33′10″E), and the northern one is 4.5 km to the north (27°35′10″S, 120°32′40″E) on a faulted contact between metabasalt and weathered foliated granitoid rock. A sample of dump material from the Bellevue gold mine (1.5 km south-southeast of townsite) assayed 0.3 per cent copper (King, 1966).

AGNEW-LAWLERS GROUP

Intermittent production between 1915 and 1958 from this group yielded ores and concentrates containing 198.75 t of copper. Some 165 t of this copper was won from the Bungarra and succeeding tenements situated 500 to 800 m north-northeast to northeast of the Bower gold workings (28°02′10″S, 120°31′20″E), which are 5.6 km north of the abandoned Lawlers townsite. Part of the description given by Low (1963, p. 153) erroneously refers to the Bower workings. At the copper workings, which are on the northern and opposite side of the valley from Bower, copper carbonates, oxides and quartz occur in a short, east-trending vein. The country rocks are east-striking, thoroughly recrystallized and locally foliated metadolerite and metagabbro.

The Lawlers West mine (28°05′10″S, 120°28′50″E) produced 118 t of copper and cupreous ore and concentrates, and is located about 500 m west-northwest of the Bounty gold mine in a flat beside a creek. The country rocks are lineated fine-grained to medium-grained amphibolities, which are chloritized adjacent to mineralization. A vertical limonite-malachite-azurite-cuprite-quartz vein up to 1 m wide strikes 185 degrees and has been opened up in the oxidized zone over a 60 m length.

Some 2.4 km southwest of the Lawlers townsite, 35.5 t of cupreous ore were mined in 1952 from a quartz vein in foliated to schistose amphibolites striking northeast. Gold workings are also present in the area.

COSMO NEWBERRY OCCURRENCE

Bunting and Chin (1975) reported copper carbonates in joints and shear planes in metabasalt 2 km west-southwest of Cosmo Newberry mission (28°00′S, 122°53′E).

WILDARA PROSPECTS

In 1967 18.2 t of cupreous ore averaging 7.68 per cent copper was extracted from three MC's (ca.28°11′20″S, 120°53′20″E) over north-northwest striking serpentinite and metabasalt, located 5 to 6 km northeast of Wildara homestead. The prospects have not been inspected.

WADGINGARRA CENTRE

The Olive Queen gold-copper mine (28°17′00″S, 116°48′10″E) produced 14.13 t of copper ore in 1906, and PA 2510 (to the northeast) yielded 2.84 t of cupreous ore in 1955. A vertical quartz vein trends 004 degrees at Olive Queen and is emplaced in massive to foliated metadolerite and metabasalt. Malachite stains occur in fractured vein quartz and in pods of massive limonite. There are two vertical shafts 20 m apart on the vein. The northern shaft contains water at 33 m, and the southern shaft is 10 m deep.

Other prospects occur in metagabbros 4 km west and 5.5 km south of the Olive Queen (Muhling and Low, 1973).

YALGOO SHEET OCCURRENCES

Muhling and Low (1973) reported two areas of occurrences in mafic rocks on the Yalgoo Sheet. At Buddadoo Range South (28°44′S, 116°29′E) copper carbonates occur at three localities near the top of the Buddadoo Gabbro, which is a metamorphosed layered intrusion. Near Mullyakko Hill (28°20′S, 116°40′E) copper minerals are present in northwest-striking metabasalt accompanied by some felsic rocks.

FITZ BORE PROSPECT

At this prospect (28°37′30″S, 118°54′00″E), a shear striking north-northeast contains a quartz vein with malachite staining visible over 80 m. An inclined diamond drillhole bored by Australian Geophysical Pty. Ltd. in a joint venture with Amad and WMC, encountered 30 cm of 0.7 per cent copper at a drilled depth of 114 m, in metagabbro adjacent to amphibolite. The drillhole was targeted on an induced polarization anomaly below the quartz vein.

LAVERTON SHEET DEPOSITS

Two small gold mines at Mount Morven (28°48′50″S, 122°10′20″E) in the Mount Margaret centre, and at Rowena (28°55′S, 122°38′E) produced 11.53 t and 2.89 t of copper ore respectively from 1906 to 1907. Both are within metabasaltic rocks, though some copper shows are in felsic metavolcanic and volcaniclastic rocks at Rowena.

MENZIES SHEET DEPOSITS

In 1961 7.55 t of cupreous ore was produced from the Forrest Belle Gold Mine (29°01′20″S, 120°30′10″E) in the Mount Ida Centre. The country rocks are north-striking metadolerite and metagabbro.

Two copper occurrences in north-striking mafic metavolcanic rocks are recorded from Mulline (29°48′S, 120°33′E) and Little Wonder (29°42′50″S, 120°33′50″E), both gold mining areas west of Menzies. Feldtmann (1915, p. 148) described a malachite-azurite-cuprite bearing quartz vein striking northwest and dipping southwest at the Mulline locality (3.2 km east of the abandoned Mulline Townsite). The Little Wonder occurrence is shown by Kriewaldt (1970) as being about 1 km south of the Little Wonder gold mine.

An occurrence in north-striking metabasalt is shown near Donna Gnamma Hole (29°11′S, 120°08′E) by Kriewaldt (1970).

NINGHAN SHEET DEPOSITS

Reported mineralization in structural sites in mafic igneous rocks is concentrated in the northwestern part of the Sheet at Warriedar copper mine (29°05′20″S, 117°07′40″E), Fields Find gold-copper mine (29°02′20″S, 117°14′30″E), Langs Find (Rose Marie) gold-copper mine (29°04′50″S, 117°07′50″E), and small copper or gold-copper mines and prospects in the Mount Gibson-Paynes Crusoe area (ca. 29°38′S, 117°10′E). The first three mines have been inspected.

The Warriedar mine is 7.2 km at 313 degrees from Warriedar homestead. It produced 2 207 t of cupreous ore averaging 9.83 per cent copper (217 t copper) in the period 1958 to 1969, which is the second largest production in the Murchison Province after the Gabanintha district. The country rocks are tholeiitic metabasalts, locally amygdaloidal, which are intercalated with northwest-striking chert-banded iron formation and metasedimentary rocks to the north. These rocks continue eastwards in an arcuate belt of hills to Fields Find where the strike is east-northeast. The metabasalt is massive in outcrop but contains subvertical fracture sets striking north-northeast, north-northwest and east-northeast.

A cupriferous-limonite-quartz vein striking north-northwest and dipping at 30 to 45 degrees southwestwards has been opened up by two underlay shafts (Fig. 47) over a length of some 100 m, mainly in oxidized and supergene mineralization. There is very little mineralization evident in outcrop. Levels are present at 18.3 and 25.0 m vertical depths. The vein is 0.40 to 1.30 m wide near the surface but averages 0.40 m at depth in the sulphide zone. The highest level is in oxidized material (malachite-azurite-chrysocolla-pseudomalachite-cuprite) which averaged about 10 per cent copper and is mainly stoped out to the surface. Supergene sulphides (chalcocite, pyrite) appear below 21 m to 27 m together with copper carbonates and chalcopyrite. An assemblage of pyrite-pyrrhotite-chalcopyrite-bornite-chalcocite has been reported from 30 m vertical depth where the average grade is about 3.5 per cent copper. The amount of quartz present is variable and the vein pinches and swells, whereas the iron-copper minerals may occur as seams, bunches or massive lenses. A weakly mineralized shear 50 m east of the mined vein was tested by a shaft (underlays at 5 m depth) and shallow costeans. Thin quartz-pyrite-chalcopyrite veinlets were found in a zone up to 0.5 m thick dipping at 65 degrees to the southwest.

In the main vein at Warriedar a little low-grade primary sulphide and some medium-grade supergene sulphide mineralization remains in the workings. However the lateral extensions of the mineralization remain undefined. The known mineralization, which is in a thin vein, below the water table, is not therefore an attractive economic proposition, though blind ore shoots could exist.

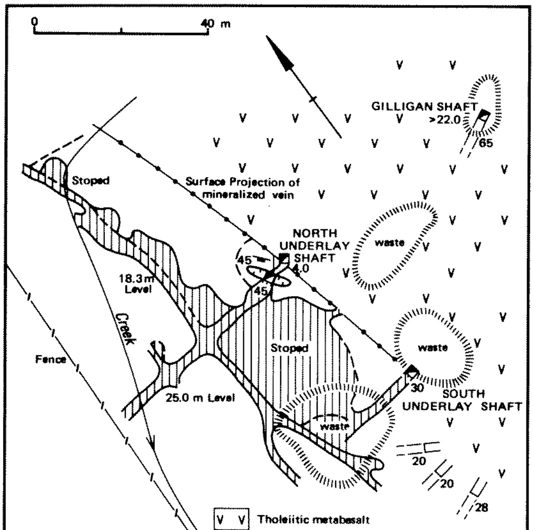


Figure 47. Surface plan and extent of underground workings at Warriedar copper mine

Langs Find is 6.7 km at 332 degrees from Warriedar homestead. It was principally a gold mine developed at the northern end of a 2 km long shear trending 026 degrees, occupied by a quartz vein up to 1 m wide. Malachite-stained mafic meta-igneous rocks can be found on some of the dumps. Intrusive granitoids outcrop to the west. In 1957 9.50 t of copper ore assaying 13.48 per cent copper were produced.

Fields Find is 12.5 km at 030 degrees from Warriedar homestead, and is adjacent to the Yalgoo road. The host rock appears to be quartzose metadolerite which, on the main waste dump, contains fracture coatings and disseminations of pyrite and lesser chalcopyrite. Weakly cupriferous limonitic quartz veins trending about 075 degrees and dipping steeply north or south, have been stoped out to the surface at two places. In 1945 30.94 t of copper ore averaging 13.39 per cent copper was produced.

The prospects in the Mount Gibson-Paynes Crusoe area are probably similar to occurrences at Fields and Langs Find. In 1915 a total of 5.07 t of copper ore was produced from sundry claims in the area.

HARRISON PROSPECT

This prospect (29°03′30″S, 115°36′50″E) occurs in a north-south gully cut through the north-northwest-trending Darling Fault, a dislocation which forms the western margin of the Yilgarn Block. In the northern part of the gully, which lies east of the fault, medium-grained biotite granitoid is seen cut by subvertical zones of foliation, cataclasis, epidotization and chloritization that strike between north and north-northwest. These shear zones are most prominent where developed in dykes and inclusions of metadolerite or amphibolite which occur within the granitoid. Thin quartz veins or silicification accompany some shear zones. One mafic dyke or inclusion that crops out as a 15 by 3 m area in the creek bed is involved in such a shear and alteration zone, and is iron stained on fracture surfaces and in patches a few tens of centimetres in size. Copper staining is rare here and at other similar outcrops, which may assay several thousand ppm copper. The shows probably represent weak supergene enrichment of disseminated pyrite and sparse chalcopyrite in small bodies of mafic meta-igneous rock, and as such are of no economic significance.

GOONGARRIE DISTRICT

Small tonnages of oxidized copper and cupreous ore (Table 32) have been produced from auriferous limonitic quartz veins emplaced in north-striking mafic to ultramafic rocks in this area (ca.30°03′S, 121°07′E)

JACKSON SHEET DEPOSITS

The Marda (Eleven Mile) mine (30°15′S, 119°12′E) exploited a quartz vein in metadolerite and metagabbro at the southern margin of an arcuate supracrustal belt in the Mount Jackson area. Some 16 t of carbonate-oxide copper ore was produced in 1942.

North-striking amphibolites at the Carterton Gold Mining Centre (30°28′20″S, 118°54′20″E) contain vertical, east-west oriented gold-copper quartz veins. Production of cupreous ore from two P.A.'s in 1950 and 1956 amounts to 66 t averaging 5.13 per cent copper.

KURNALPI SHEET DEPOSITS

Williams (1970, p. 31) noted the following deposits:

(1) Hopeless Dam (30°22′S, 122°37′E): copper show in metabasalt;

(2) Corsair (30°45′50″S, 121°36′20″E) gold mine produced 8.15 t of copper contained in 81 t of copper and cupreous ore; the mine occurs in a thin quartz vein in a thin pelitic metasedimentary band within north-northwest striking mafic to ultramafic rocks; and

(3) Emu Dam (30°51′30″S, 121°54′00″E): small copper gossans developed in quartz veins filling fractures in north-striking magnetite-rich metadolerite.

BEECK PROSPECT

Discontinuous shows of primary and secondary copper and iron minerals have been reported over a 900 m strike length at this prospect (ca. 30°30′S, 121°15′E), 1.5 km west of the 27 mile peg on the Kalgoorlie-Leonora road. The country rocks are north-northwest striking mafic to ultramafic meta-igneous rocks with silicified slate bands, and the host rock is a serpentinite. The mineralization has a carbonate and chalcedonic silica gangue and appears to be developed in a shear zone paralleling the strike. Individual mineralized lenses are only up to 20 m long and 40 cm wide.

WONGAN HILLS DISTRICT

Small quartz veins and lenses carrying copper carbonates and oxides have been reported from the central part of the range (ca. 30°50′S, 116°37′E) by Maitland (1899, p. 33). The host rocks are north-striking amphibolites.

PARIS GOLD-COPPER MINE

From 1960 to 1964 copper was produced from gold concentrates mined here (31°35′20″S, 121°58′20″E), totalling 191.50 t of copper.

Quartz veins in metadolerite carry gold plus pyrite, pyrrhotite, chalcopyrite and arsenopyrite, and the same mineral assemblage may occur as masses or disseminations in the host rock (Ward, 1965). The veins are related to steeply dipping shears trending 290 to 295 degrees, but in detail the ore shoots coincide with folded quartz veins which apparently pre-date these shears. There are no significant supergene concentrations of copper.

HIGGINSVILLE PROSPECT

In 1963 and 1965, 73 t of cupreous ore were extracted from this prospect (31°40′30″S, 121°41′50″E), which is in north-northwest striking and steeply east-dipping ultramafic schist and metasedimentary rock. Malachite, azurite and minor cuprite in limonitic veins and lenses have been opened up in shallow excavations over a north-south oriented zone 100 m long and 18 m wide (Sofoulis, 1962).

MOUNT THIRSTY SILL OCCURRENCE

Doepel (1973, p.29) reported copper gossans occurring just above the base of the Mount Thirsty Sill, a metamorphosed layered mafic-ultramafic intrusion (32°05′S, 121°39′E).

LAKE DUNDAS PROSPECT

At this prospect (32°26′20″S, 121°49′30″E), a laminated quartz vein up to 3 m thick and striking north-northeast has been pitted and costeaned for 250 m. The vein parallels the foliation in tholeiitic metabasalt and metadolerite which dips at 55 to 65 degrees to the west. The wall rocks are silicified over 5 to 10 widths and the vein is probably a replacement type. Malachite and azurite occur as foliation and fracture coatings in the silicified zone. No production has been recorded and the mineralization is very weak.

NETTY COPPER MINE

Small copper workings (33°52′30″S, 118°57′50″E) are located in a farm paddock, 600 m west-northwest of Rocklea Park homestead in the Jerramungup area. The workings (now largely collapsed) are sited on the southern margin of an east striking mafic dyke which varies from a medium-grained leucocratic gabbro in the centre to finer grained dolerite at the margins. The dyke intrudes a foliated, biotite-rich granitoid containing lensoid megacrysts of potassium feldspar. Mineralization cannot be seen *in situ* but rock fragments indicate that a thin, quartz-poor, cupriferous limonite vein occurred at the contact. Supergene redistribution has given rise to copper-stained fractures in the dyke and the granitoid. The mine was worked in 1907, 1955 to 1956, 1962 and 1969 for copper and cupreous ore containing a total of 3.13 t of copper. The mineralization is of little economic significance.

OTHER HOST ROCKS

TWIN PEAKS DEPOSITS

This small group of workings (27°22′30″S, 115°58′50″E) occurs in a small belt of northeast-striking, complexly deformed amphibole-bearing psammitic to pelitic schists, siliceous amphibolite, mafic amphibolite and various granitoid intrusives. The area has been described by Sofoulis and Williams (1970) who give an oversimplified and highly interpretive account of the geology. All rocks except porphyritic granodiorite intrusives and porphyritic dolerite dykes are highly deformed and probably in the amphibolite facies of regional metamorphism. Two schistosities are present in many of the striped semi-pelitic schists and siliceous amphibolites. Steeply plunging mineral and intersection lineations are common.

Material on the dump adjacent to the main shaft (17.5 m deep and dry) comprises quartz-muscovite-chlorite schist, biotite-quartz-feldspar schist, biotite granodiorite, thin veins of cupriferous limonite and copper-stained schist. Surface expressions of mineralization are feeble, and available exposures indicate that very thin limonite veins and lenses are structurally located in northeast-striking, subvertical shears. The pyroclastic rocks described by Sofoulis and Williams (1970) are not clearly recognizable, and the post-tectonic aspect of the granodiorite prohibits any genetic relationship with the mineralization which appears to have been deformed and recrystallized. Many of the rocks southeast of the mineralized zone (discontinuous over 200 m) are epidotized and variably silicified. There is also some weak shear-located mineralization in, or marginal to, a north-northeast striking dyke of porphyritic hornblende-biotite granitoid to aplite, to the west of the main shaft. Copper and cupreous ore, mostly from the oxidized zone, was mined in 1906 to 1908, 1949 and 1951 to 1955 and totals 8.47 t of contained copper. The mineralization does not appear to be of any great economic importance.

CUDDINGWARRA NORTH PROSPECT

A collapsed stope 5.5 m deep was opened up in cupriferous limonite lenses up to 20 or 30 cm wide at this prospect (27°18′30″S, 117°47′30″E). The lenses parallel the foliation in kaolinized, fine-grained felsic volcaniclastic rocks and carbonaceous phyllite in contact with metabasalt to the east. The strike of the foliation is 010 degrees, the dip 70 degrees eastward. Simpson and Gibson (1907, p. 27) reported a production of some 5 t of copper ore averaging 25 to 30 per cent copper, but there is no official record of this.

MOUNT EELYA DEPOSIT

The deposit referred to by Low (1963, p. 128-129) was not located (ca. 27°19′S, 118°08′E). Some 6 t of cupreous ore was produced in 1955 from a shallow pit on a poorly exposed, east striking quartz vein near the old gold mining centre of Eelya. The country rocks are sheared quartz-eye metarhyolite intruded by metagabbro-dolerite and equigranular adamellite.

BARRAMBIE MINE

Barrambie mine (27°31′10″S, 119°11′00″E) occurs in an open flat 200 m west of the abandoned Barrambie homestead, on the western side of a narrow, north-northwest-striking supracrustal belt. Outcrop to the northeast of the mine is of massive, medium-grained anorthositic metagabbro followed eastwards by strongly lineated quartz-feldspar-mica-chlorite schist. The rocks exposed in the mine openings appear to be very weathered and kaolinized versions of this schist. Some rocks contain opalescent eye-shaped quartz and may be of volcanic origin.

A laminated quartz vein 1 to 4 m wide, that strikes at 322 degrees and dips steeply to the west or east, contains lenses, stringers and veinlets of malachite and chrysocolla. The vein has been opened up over 40 m at the surface by shallow collapsed shafts at each end of a 3 (originally 8)-m-deep open cut. Two shafts 12 to 13 m deep and 55 m south of the open cut, encountered quartz chlorite schist with malachite-chrysocolla fragments. Low (1963, p. 147-148) reported that the main ore body was 13 m long and was worked to 30 m depth (to within 6 m of the water table). Copper and cupreous ore containing 137.70 t of copper were produced in 1944 and 1956 to 1961. The ores contained minor amounts of silver and a trace of gold.

LAVERTON SHEET OCCURRENCES

Gower (1974) mentioned occurrences at (i) Mitika Well (28°03′30″S, 122°56′00″E) where a cupriferous quartz vein is within granitoid rocks marginal to mafic meta-igneous rocks, and (ii) near Camel Hump (28°12′30″S, 122°19′00″E) within felsic metavolcanic rocks.

IRWIN HILLS PROSPECT

Bunting and Boegli (1974, p. 21) described a 2 m wide band of phyllitic metasedimentary rock at a locality (29°09′30″S, 123°02′00″E) 3.5 km west-southwest of Jasper Hill, containing smithsonite, malachite and minor azurite. The strike is north-northwest and the visible mineralization is present over 100 m, being gossanous over 35 m. The phyllite is chloritic and may be tuffaceous in part, and is part of a sequence of chert, black slate, jaspilite, and mafic to ultramafic meta-igneous rocks. The prospect has not been inspected but it appears to coincide with or be near former PA 1688 which in 1967 produced 9.24 t of cupreous ore averaging 14.40 per cent copper.

LADY BOUNTIFUL AREA

Several small prospects occur in this old gold mining area (30°30′20″S, 121°12′00″E), within a poorly exposed unit of black slate and other metasedimentary rocks, that is a subordinate component of a northwest-striking mafic meta-igneous sequence. Cross-cutting quartz veins contain limonite, malachite, cuprite and chrysocolla. In 1953, and 1955 to 1956, 35 t of cupreous ore averaging 9.11 per cent copper were produced from the area.

MOUNT PLEASANT DISTRICT

There are two areas in this district in which copper was worked, in flat ground to the south and east of north-northwest striking hills of mafic and meta-igneous rocks. The Old Mount Pleasant mine (30°31′40″S, 121°15′40″E) is 150 m southeast of the Black Flag-Broad Arrow track. It consists of two easterly inclined, (collapsed) shafts in a north-striking, thin unit of black slate and felsic metasedimentary rock, intercalated in metagabbro (west) and talc-carbonate, amphibole-chlorite rocks (east). Thin veins of copper-stained limonite occur on the dumps. In 1960-1962, 83 t of cupreous ore averaging 7.55 per cent copper were produced. Gold workings occur to the south, and a series of 2-m-deep costeans trace the metasedimentary unit northwards across the track.

About 1 km to the northeast is the New Mount Pleasant mine (30°30′30″S, 121°15′50″E) which was developed in 1973 to 1974 by Odin Mining and Exploration Pty Ltd. A shaft was sunk and cross cut to intersect the northern end of a thin, north-striking unit of black slate, phyllite and possible tuffaceous metasedimentary rocks between metagabbro (west) and a pale green, feldspar-rich intermediate metavolcanic rock containing sparse pyrite. This unit was prospected and drilled (twelve percussion holes and nine diamond holes) by Great Boulder in 1971 to 1973, who stated that a 210 m long, steeply dipping mineralized zone 0.9 to 7.6 m thick at depths between 29 m and 76 m had been located. The mineralization is oxidized and consists of copper carbonates, oxides, native copper, bornite and chalcocite, averaging about 5 per cent copper and amounting to an indicated resource of some 70 000 t. The primary sulphides (pyrite-chalcopyrite-minor sphalerite) would probably only average 1 per cent or less copper with minor silver and zinc.

Mineralized material on the dumps includes quartz-cemented slate-phyllite breccia, with supergene sulphides in clots and veinlets, and crudely foliated massive limonite-supergene sulphides with variable amounts of quartz gangue. The shaft is 83.8 m deep (33.7 m to water) and levels were established at 69.2 m and 76.2 m depths in chalcocite, bornite, cuprite and native copper mineralization. The bulk assay of 90 t of material extracted from driving on the 76.2 m level was 6.26 per cent copper (1.5 per cent cut off) and 91 g/t silver.

NICKEL-COPPER DEPOSITS (TYPES E AND F)

COPPER-DOMINATED MINERALIZATION

Although trace amounts of iron-nickel-copper sulphides occur in some gabbroid complexes, even sub-economic occurrences containing more copper than nickel are very rare. The Youangarra (Currans Well) prospect (28°47′S, 118°43′E) is an example in the Youanmi area. Copper-nickel gossans occur in a metamorphosed gabbro-pyroxenite intrusion intruding poorly exposed metasedimentary rocks. Most gossans were found to correspond to pyrrhotite and pyrite, but one of two diamond drillholes put by WMC encountered a drilled width of 8.18 m assaying 0.62 per cent copper and 0.33 per cent nickel.

NICKEL-DOMINATED MINERALIZATION

On the basis of host rock type and nickel-copper ratio, deposits of this type fall into three groups as follows (Binns, Groves and Gunthorpe, 1976).

(i) Deposits in meta-dunitic intrusions with nickel:copper in the range 25 to 60 (e.g. Mount Keith).

(ii) Deposits in meta-peridotite flows or sills in komatiitic volcanic piles with nickel:copper in the range 10 to 20 (e.g. Kambalda).

(iii) Deposits in layered peridotite-gabbro intrusions with low nickel:copper (Carr Boyd Rocks complex).

Type (ii) deposits, in particular the Kambalda group (Ross and Hopkins, 1975), have provided important quantities of by-product copper in concentrates (Table 3). The only deposit that will be briefly mentioned here is that in the Carr Boyd Rocks complex, the only representative of type (iii).

Carr Boyd Rocks mine (30°04′S, 121°38′E) is 80 km north-northeast of Kalgoorlie. The mine is on the western side of a 75 km² metamorphosed layered intrusion of dunite, harzburgite, bronzitite, troctolite, norite and olivine anorthosite of tholeiitic affinities (Purvis and others, 1972). The mineralization occurs in intrusive breccia pipes, which in turn are within an east-northeast trending zone of bronzite pegmatoids. Three, breccia pipe ore shoots 20 to 60 m in maximum plan dimension have been outlined by Great Boulder-North Kalgurli since discovery in 1969. The primary ore consists of 70 per cent silicate xenoliths and xenocrysts, 20 per cent pyrrhotite, 4 per cent pentlandite, 2 per cent chalcopyrite and 2 per cent pyrite. Production began in mid-1973 and until closure in mid-1975 amounted to 178 427 t averaging 1.43 per cent nickel and 0.46 per cent copper (Ni:Cu=3.11). Production was resumed in March 1977 by WMC who estimated demonstrated reserves as 552 000 t averaging 1.51 per cent nickel and 0.49 per cent copper.

LEAD-ZINC-COPPER OCCURRENCES

Blockley (1971b, p. 198-200) mentions three occurrences where copper carbonates or chalcopyrite accompany galena and sphalerite in quartz veins emplaced in granodiorite or gneiss in the Darling Range southeast of Perth. These are 1.6 km southeast of Armadale (32°11′S, 116°02′E), 3.2 km east of Mundijong railway station at Mundijong lead mine (32°19′S, 116°01′E), and at Serpentine (32°22′S, 116°00′E).

OTHER OCCURRENCES

Minor amounts of copper minerals accompany molybdenum and/or tungsten minerals in quartz veins (commonly in granitoid rocks) at the following occurrences (Baxter, in press).

1. Argus show (30°22′20″S, 121°05′00″E): tungsten plus copper, lead.
2. Boyagarra (32°17′50″S, 117°10′40″E): tungsten plus copper.
3. Callie Soak (27°16′40″S, 117°31′00″E): tungsten plus molybdenum, copper.
4. Colemans (33°36′S, 119°59′E): molybdenum plus copper.
5. Mertondale (28°38′20″S, 121°22′40″E): molybdenum plus copper, lead, zinc. copper.
6. Molybdenite show (27°16′40″S, 117°30′50″E): molybdenum-tungsten plus copper.
7. Recovery (27°16′50″S, 117°31′00″E): molybdenum-tungsten plus copper.

CHAPTER 17

Northampton Block

SUMMARY AND CONCLUSIONS

The Northampton Block extends over 3 700 km^2, and except in the south it is surrounded by onlapping Phanerozoic sedimentary rocks of the Carnarvon and Perth Basins. High-grade metamorphic rocks and granitoid intrusives make up the block, and granulite samples yielded an Rb-Sr isochron of 1 040 ± 50 m.y. (initial $Sr^{87}/Sr^{86} = 0.721$) according to Compston and Arriens (1968). These rocks are intruded by a suite of north-northeast-trending, steeply dipping or vertical dolerite dykes, which have not been satisfactorily dated. Northwesterly striking granulites make up the bulk of the exposed part of the block, and consist mainly of banded quartz-microcline-plagioclase-garnet-biotite granulite which locally contains cordierite, sillimanite and green spinel (Peers, 1971). Thin units of deformed and coarsely recrystallized quartzite and conglomerate, and two-pyroxene-plagioclase-biotite granulite are rare. Pyrite, graphite and zircon are common accessory minerals. The chemical composition of the common granulites (Prider, 1958), the presence of quartzites and conglomerates, and the presence of graphite and rounded, relict detrital zircon grains (Peers, 1971), indicate that the original rocks were sedimentary, and largely of greywacke composition.

Lead, copper, zinc and silver mineralization occurs almost exclusively in the granulites, within short sections of more persistent fractures, faults or shears (Blockley, 1971b, p. 38). These dislocations generally strike north-northeast (parallel to the dolerite dykes), but may follow other directions or the compositional banding of the granulites. Blockley (1971b) found that only 30 per cent of the mines and prospects were closely associated with dolerite, and none of these were major producers of lead or copper (with the possible exception of Gwalla copper mine). The ore shoots are commonly in the range 15 to 270 m long, and they occur in the curving or branching parts of the fractures as vuggy, quartz-cemented breccia zones 0.3 to 3 m wide and, exceptionally, 9 m wide (Blockley, 1971b, p. 38-39). The shoots in turn consist of lenticular mineralized veins up to 1 m wide, which occupy tensional openings within the breccia zones, and are mainly composed of fine-grained to coarse-grained, massive sulphides (galena, sphalerite, pyrite, marcasite and chalcopyrite), which are typically vuggy in texture. None of the ore shoots worked have been found to persist below 170 m depth, and the majority bottomed at about 90 m or less. Marginal alteration (e.g. chloritization of garnet, uralitization of pyroxene) is present in wall rocks to some mineralized fractures, but similar alteration is also found in unmineralized fractures distant from mines.

Lead and copper have generally been mined from separate ore shoots, and where mined at the same locality copper occurs in one part of the mineralized zone whereas lead occurs in another (e.g. Narra Tarra), S. S. Michael (pers. comm. 1977) has found that chalcopyrite is not in equilibrium with the galena and sphalerite. There is also textural evidence that the copper mineralization post dates the lead-zinc mineralization (e.g. Wilson, 1926, p. 24). Copper producing mines are shown in Figure 48 and production statistics are summarized in Table 37. The mines are in three groups which, from north to south, are at (a) Murchison River (near Galena townsite—now abandoned), (b) at Northampton, and (c) in a southern district. The major copper producing mines were Gelirah, Geraldine, Gwalla, Narra Tarra, Narra Tarra East, Wanerenooka, Wheal Fortune, Wheal Margaret and Yanganooka.

It is improbable that economically recoverable copper mineralization remains in any known ore shoots. Blockley (1971b, p. 39) suggests that undiscovered blind shoots may extend to depths below the maximum to which mineralization has previously been found (i.e. 170 m). If they exist, such shoots would be difficult to detect, and although primary sulphides may be medium grade (5 to 6 per cent copper), the narrow and variable form of such fissure-vein mineralization does not make it an attractive economic proposition. The mineral rights are largely alienated from the Crown, and mining costs for deep, narrow, steeply dipping veins would be prohibitive in most cases.

MINERALIZATION (TYPE C)

COPPER MINES AND PROSPECTS

GELIRAH MINE

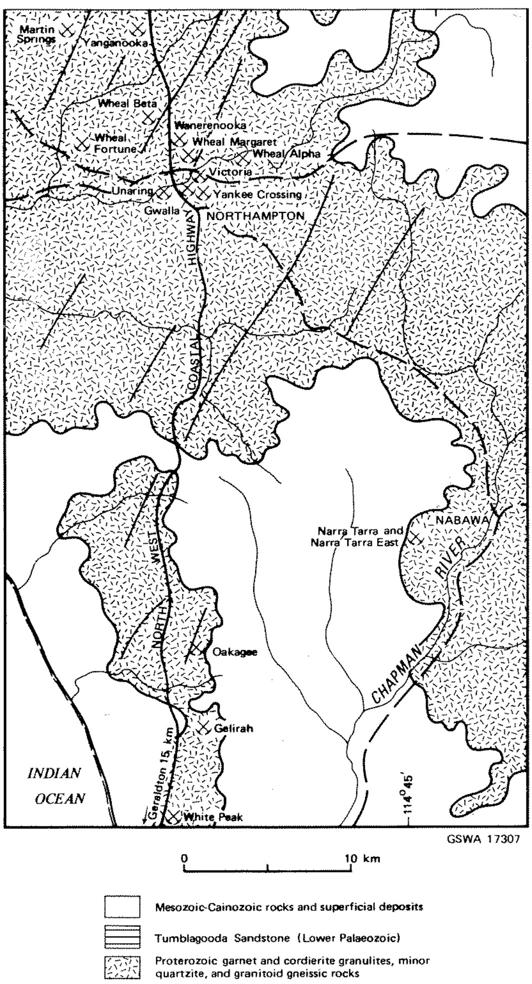
Gelirah mine (28°35′40″S, 114°39′00″E) is in the southern district and consists of two parallel ore veins striking 043 degrees and dipping steeply west. A substantial (but unknown) amount of ore was raised from the eastern vein which was opened up over a 75 m length, though the mineralization was traceable for 270 m. The shafts were originally 36.6 m deep and the vein was 0.60 to 1.80 m wide. Blockley (1971b) took a sample over a 90 cm width which assayed 11.5 per cent copper, 0.42 per cent lead and 0.26 per cent zinc. The western vein is 180 m long and up to 46 cm wide and was worked for lead and copper. A sample over 91 cm width assayed 1.81 per cent copper, 0.17 per cent lead and 0.35 per cent zinc (Blockley, 1971b). Chalcocite, azurite, malachite, galena and sphalerite have been recorded from the mine.

GERALDINE MINE

Geraldine (Geraldine North, Mitchells, Four Mile Pool) mine (27°50′50″S, 114°38′10″E) is in the Murchison River area, immediately west of the North West Coastal Highway. Five shafts, originally 9.8 to 42.7 m deep are distributed along a 50 m long line, on a subvertical, northeast-trending dolerite dyke emplaced in siliceous garnetiferous granulite. The mineralized zone is 3 to 6 m wide and consists of (i) dolerite and granulite breccia cemented by massive cupriferous limonite and quartz, which is vuggy in parts, and (ii) lenses up to 2 m wide of massive, weakly copper-stained limonite within bleached dolerite. Levels were established at 18.3, 32.9, 34.4 and 42.7 m depths. Galena, sphalerite and chalcocite were reported from the 42.7 m level, and veins of chalcocite and native copper 15 to 30 cm wide were found on the 18.3 m level. Production recorded in 1899-1901 was 138.69 t of ore and concentrates averaging 26.40 per cent copper (36.04 t copper) which also included 15 to 20 kg of silver.

GIBSONS PROSPECT

This prospect (27°48′30″S, 114°42′30″E) is 3.6 km northeast of the Murchison River bridge. A shaft 12 m deep was sunk on a rich vein 5 cm wide at the surface and 46 cm wide at the base of the shaft (Wilson, 1926, p. 20).



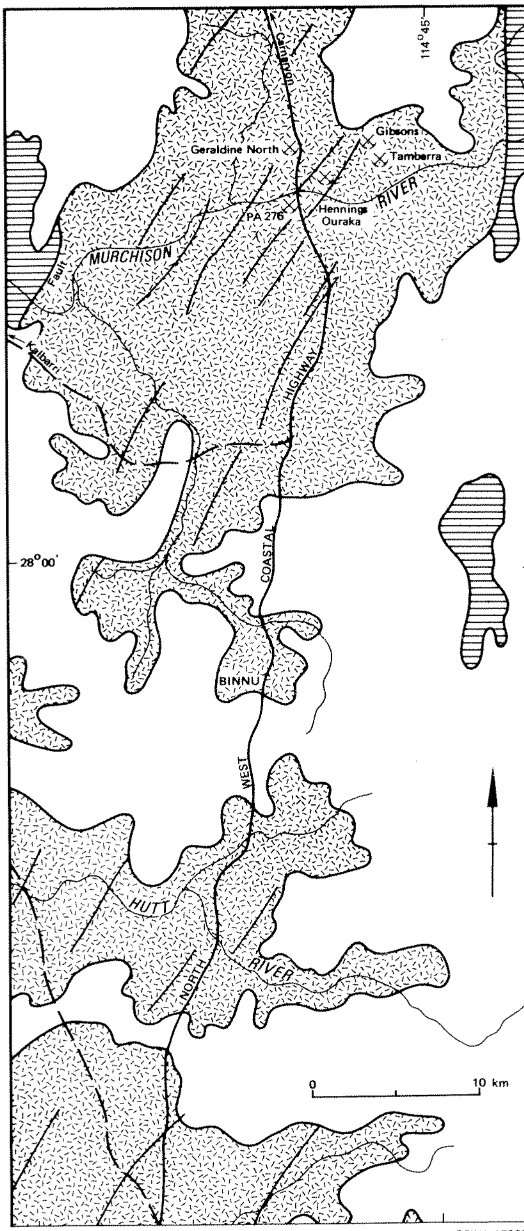


Figure 48. Generalized geological map of part of the Northampton Block showing mines with recorded copper production

GWALLA MINE

The Gwalla mine (28°21'50"S, 114°38'20"E) is in the Northampton townsite, and is the northern extension (on north side of highway) of the Camp Hill workings. There are two parallel ore bodies striking about 035 degrees and dipping steeply or vertically. The eastern deposit was opened up to 54.9 m depth, and 200 m of driving and stoping was done on the 32.9 m level. Veins of bornite up to 23 cm wide, and seams of chalcocite and chalcopyrite were found. The ore contained a little silver (less than 30 g/t). Production recorded in 1863-1868 was about 916 t of ore averaging 13.50 per cent copper (123.7 t copper).

HENNINGS PROSPECT

Hennings prospect (27°49'10"S, 114°42'10"E) is immediately north of Ouraka prospect, and 1.8 km northeast of the Murchison River bridge. Wilson (1926, p. 20) reported that about 5 t of ore was raised from a small but rich vein here.

MARTINS SPRING MINE

This mine (28°17'30"S, 114°34'50"E) is 120 m north-northeast of Scott and Gales mine, in the Northampton area. Two shafts originally 15.2 and 12.8 m deep are 18 m apart on an east-west line. The dumps contain abundant garnet granulite and pegmatite, some of which is copper stained, and small fragments of limonite, malachite and azurite. No vein quartz or dolerite is visible. The ore contained lead and up to 1 576 g/t silver.

NARRA TARRA MINE

Narra Tarra mine (28°30'30"S, 114°44'50"E) is located 3.9 km at 260 degrees from Nabawa, at the old townsite (now abandoned) of Protheroe (Fig. 49). The mine has been the principal copper producer in the block having supplied 24 266 t of ore averaging 7.53 per cent copper (1 825 t copper) in the years 1922 to 1925 and 1929. In addition to this the ore produced in the first period also yielded 642.90 kg of silver and 2.84 kg of gold. Production ceased because of a marked drop in the grade of mineralization in the lowest levels. The copper-rich part of the mineralized zone was discovered some 50 years after mining for lead took place in 1874-1880.

The mineralized shear containing the mine strikes 030 degrees and dips at 70 degrees to the east. Dolerite is not present in the shear in the mine area. The country rocks are north-northwest-striking, banded garnetiferous granulites which are coarse grained or biotite-rich in parts. Dips are steep, but minor folds which appear to plunge shallowly northwestwards are visible in the sides of the open cut. Small ridges of medium to coarsely recrystallized quartzite in the general area appear to define a major north-northwest oriented fold (Fig. 49).

Copper was mined from the southern end of the shear, and lead from the northern end. About 120 m south of the main shaft the lead mineralization changed abruptly to copper. Veins occurred in a 6 to 9 m wide breccia zone and were opened up on levels at 13.7, 32.0, 50.2, 76.2, 106.6, 137.1 and 167.6 m depths. Ore shoots plunged steeply southwards. Limonite, quartz, malachite, azurite and chalcocite can be found around the open cuts and shafts. The mineralization is oxidized to a 30 m depth which is unusually deep for the Northampton Block (Blockley, 1971b). Old tailings dumps sampled in 1965 (King, 1966) yielded an assay of 1 per cent or more lead, 0.08 per cent copper and 0.06 per cent zinc.

NARRA TARRA EAST MINE

This mine (28°31'00"S, 114°44'50"E) is 600 m south of the open cut at Narra Tarra (Fig. 49), on a mineralized shear striking 040 degrees and dipping steeply west. This shear is reported to be an extension of that containing the lead mineralization at Protheroe

TABLE 37. MINE PRODUCTION OF COPPER FROM THE NORTHAMPTON BLOCK

Mine	Copper ore and concentrates (t)	Cupreous ore and concentrates (t)	Average grade (%)	Contained copper (t)
Gelirah	[a]			
Geraldine	[a]138.69		26.40	36.04
Gibsons	[a]			
Gwalla	916.50		13.50	123.70
Hennings	[c]5.0			
Martins Spring	[a]			
Narra Tarra	24 265.91		7.53	1 825.58
Narra Tarra East	[a]			
Ouraka	[a]7.19		8.62	0.62
Tambarra				
Unaring	[a]			
Victoria	[a]			
Wanerenooka	[a]9.59		14.91	1.43
Wheal Alpha	[a]			
Wheal Beta	[a]			
Wheal Fortune	2 681.35		17.00	455.83
Wheal Margaret	[a]			
White Peak	[a]			
Yanganooka	465.35		[b]25.00	[b]116.00
Yankee Crossing	[a]			
Unassigned production during 1853-1898	4 840.15		[b]35.25	[b]1 706.00
Sundry Crown Lands		27.81	7.40	2.06
PA 276		7.30	12.97	0.95
Totals	33 329.73	35.11	[d]12.79	4 268.21

a. Individual production during 1853-1898 unknown, forms part of the unassigned production total of 4 840.15 t (exported ore only).

b. Estimate only.

c. Prospecting workings only but a few tonnes of ore have been produced.

d. Average for copper and cupreous ore combined.

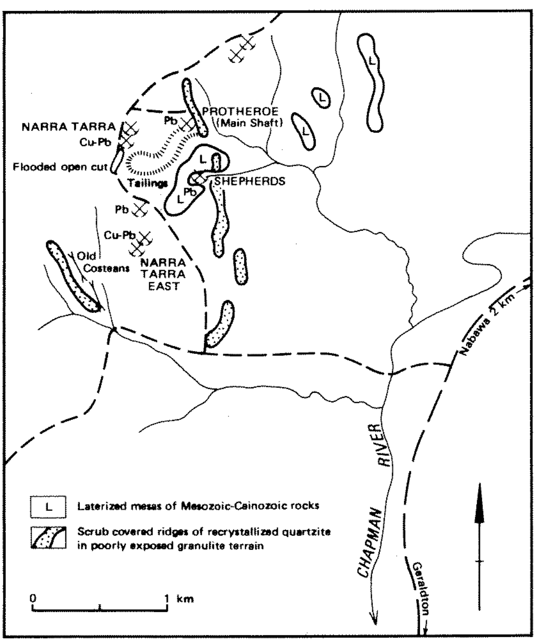


Figure 49. Sketch plan of the Narra Tarra-Protheroe mine group

mine (Blockley, 1971b). The mine was worked initially for secondary copper ore, prevalent on the hanging wall side of the shear at its southern end, and during the period 1874 to 1880 lead ore was mined. A 3 to 4 m wide zone of breccia contains 60 to 90 cm wide veins of limonite, lead and copper carbonates worked down to about 20 m depth in the south. Narrow fissure veins of quartz and pegmatite can be seen emplaced in the shear. The country rocks are similar to those at Narra Tarra mine.

OURAKA PROSPECT

Ouraka prospect (27°49′20″S, 114°42′10″E) is 1.7 km east-northeast of the Murchison River bridge. Wilson (1926, p. 20) reported that a shaft was sunk to 24.4 m on a copper show. A small tonnage of copper ore was mined in 1940.

TAMBARRA PROSPECT

Tambarra prospect (27°49′00″S, 114°43′20″E) is 3.7 km east-northeast of the Murchison River bridge. A shaft has been sunk to 4.6 m on a small, but rich vein (Wilson, 1926).

UNARING MINE

This mine is 1 km west of Gwalla mine on the south side of Northampton townsite. Shallow workings extend for 60 m in a north-northeast line, in a steeply east-dipping fracture. The workings were up to 17.7 m deep. Copper carbonates, gneiss, pegmatite and dolerite occur on the dumps.

VICTORIA MINE

Victoria mine is 1 km northeast of Gwalla mine on the eastern side of Northampton townsite. A line of shallow workings extends north-south for 244 m. Two shafts 24 m apart were sunk to a maximum of 21 m (water at 4.6 m) at the northern end of the line. Azurite, malachite and cuprite are recorded from shallow depths, the mineralization being very pyritic lower down.

WANERENOOKA MINE

Wanerenooka (Roger Malray) mine (28°20′20″S, 114°37′40″E) is on the northern margin of the Northampton townsite, immediately east of the highway, and is now the site of the town's water supply. Productive copper mining in the State began here in 1856, but the production for the period 1856 to 1868 is unrecorded. A small tonnage of ore was mined when the mine was dewatered in 1957.

The country rocks are medium-grained garnetiferous gneisses containing subconcordant pegmatites and zones rich in feldspar porphyroblasts. Intrafolial folds were noted but the general attitude of the foliation is 320 degrees strike and 30 degrees dip northeastwards. A line of shallow workings and collapsed stopes extends for 80 m in a direction trending 040 degrees, with a steep dip to the northwest. Cupriferous limonite-quartz veins up to 15 cm wide can be seen in the workings. The dumps contain (a) siliceous breccia with fine-grained disseminated pyrite, the pyrite may also form a matrix to country rock and 1 to 55 mm size fragments of galena, (b) copper-stained aplite and quartzose pegmatite (c) granulite and (d) siliceous veins with vuggy quartz, coarse galena and fine-grained pyrite-chalcopyrite.

Blockley (1971b) states that lead mineralization is present only on the hanging wall side of the 8.2 to 11.8 m wide mineralized zone, and that copper ore was worked in 30 cm wide veins on both footwall and hanging wall. Underground levels at 24.3, 42.6 and 54.8 m were developed from a 73 m deep shaft, over a maximum length of 120 m. The configuration of the stopes suggests that the ore shoots plunged to the northeast. In 1963 Dowa Mining drilled three vertical diamond drillholes totalling 187 m into the mineralized zone from the hanging wall side. Only the first two holes (collared 26 m and 56 m north-northeast of the main shaft) were deep enough to intersect this zone. One hole intersected 3.1 m of disseminated chalcopyrite in quartz and the second hole was barren.

WHEAL ALPHA

Wheal Alpha (28°20′50″S, 114°39′30″E) is on the eastern side of Northampton. Pits and shafts, originally up to 18 m deep (water at 4.6 m) extended over a 90 m length along a north-northeast trending fracture which dips west at 70 degrees. Copper carbonates and sulphides have been recorded.

WHEAL BETA

The workings here (28°19′30″S, 114°37′10″E) occur northwest of Northampton, and fall into two groups 800 m apart situated within or marginal to a single dolerite dyke striking 035 degrees and dipping steeply west. At the northern workings three shafts (now up to 8 m deep) over 43 m of strike encountered a 30—60-cm-wide mineralized fracture containing (i) vuggy vein quartz with pods and fracture fillings of limonite, azurite and malachite, and (ii) brecciated dolerite cemented by quartz, limonite, malachite and pyrite. Shallow pits, collapsed shafts and open cuts extend over 125 m strike at the southern workings where a weakly mineralized, 50-cm-wide siliceous zone is visible on the western margin of the dyke. The dyke is brecciated and veined near the workings.

WHEAL FORTUNE

The Wheal Fortune (28°20′40″S, 114°35′10″E) is west of Northampton and just north of the Port Gregory road. The mine was a major copper producer in the period 1862 to 1868, when 2 681 t of ore and concentrates averaging 17 per cent copper (456 t copper) were exported. The country rocks are quartz-feldspar-biotite-garnet gneisses containing pegmatitic lenses and veins, and clusters of porphyroblastic garnet. The foliation may be sinuous, but generally strikes about 350 degrees and dips steeply east.

The mine is at the southern end of a fracture trending 040 to 050 degrees which is vertical or dips at 70 degrees to the southeast. Levels were established at 14.6, 54.8, 73.1 and 94.1 m depths from a 91 m deep shaft. On the 54.8 m level, 223 m of driving was done, and ore stoped out above this level is reported to have averaged about 8 per cent lead and 3.5 per cent copper. Lead mineralization first appears on this level 98 m northeast of the shaft. On the 73.1 m level the ore shoot was 60 to 90 cm wide and averaged 6 per cent copper. The richer sections occurred where the fracture cut pegmatitic rocks. A sample of the tailings dumps taken in 1964 (King, 1966) assayed 1 per cent lead, 0.4 per cent zinc and only 0.05 per cent copper.

The ozidized-supergene ore assemblage is cerussite, malachite, azurite, chalcocite, covellite and native copper, whereas the primary ore consists of galena, sphalerite, chalcopyrite and pyrite occurring in vuggy vein quartz. There is no visible sign of wall-rock alteration in primary ore material found on the dumps. Workings at Wheal Fortune Extended, 150 m to the northeast on the same fracture, were largely in lead mineralization.

WHEAL MARGARET

This mine (28°20′50″S, 114°38′10″E) is on the eastern side of Northampton townsite. A fracture striking northeast and dipping at 75 degrees to the southeast, has been opened up by over an 82 m length by five shafts originally up to 53 m deep. A vein 17 to 60 cm wide containing copper carbonates and sulphides was stoped over a 61 m length.

WHITE PEAK

White Peak mine (28°38′20″S, 114°37′30″E) is in the southern district, a short distance east of the highway. The mine was opened in 1852 and some rich ore was worked before 1858.

YANGANOOKA

Yanganooka mine (28°17′30″S, 114°37′00″E) is north of Northampton and immediately west of the highway. Two parallel mineralized zones striking northeast and dipping steeply northwest occur close to a dolerite dyke. The western one was exploited by several shafts (deepest originally 54.9 m) and levels. Maitland (1903) mentioned a production of some 465 t of ore and concentrates averaging about 25 per cent copper (116 t copper).

YANKEE CROSSING

This small mine (28°21′50″S, 114°38′30″E) is immediately east of Gwalla mine on the southern side of Northampton townsite. A small, rich shoot was worked to a depth of 12 m.

LEAD MINES CONTAINING MINOR COPPER

A list of these mines is given in Appendix 3. Further details are available in Blockley (1971b)

CHAPTER 18

Proterozoic cover rocks: western and southern margins of Yilgarn Block

GEOLOGY

The lithological features and age relationships of the various clastic sedimentary rocks, cherts, mafic volcanic rocks and rare carbonates in this category are summarized by Low (1975). Outcrop areas of the various stratigraphic units are unconnected with each other. This has resulted in a proliferation of lithostratigraphic nomenclature because inter-relationships have not been established. In anticlockwise sequence commencing in the northwest the units are as follows:

(a) Badgeradda Group and Nilling Beds (Byro and Murgoo Sheets mainly).
(b) Wenmillia Formation (Geraldton Sheet).
(c) Billeranga Group and Dudawa Beds (Perenjori Sheet).
(d) Yandanooka Group (Perenjori Sheet).
(e) Moora Group (Perenjori and Moora Sheets).
(f) Cardup Group (Pinjarra Sheet).
(g) "Stirling-Barren Series" (Mount Barker, Bremer Bay, Newdegate and Ravensthorpe Sheets).
(h) Woodline Beds (Widgiemooltha Sheet).

With the exception of unit (g) which becomes involved in the Albany-Fraser Province, the rocks comprising these units are little deformed or metamorphosed. Available evidence suggests a Middle or Upper Proterozoic age for these units.

MINERALIZATION (TYPES B AND C)

Cupriferous mineralization is recorded from rocks of the Wenmillia Formation, Billeranga Group, and the Yandanooka Group. These units are essentially similar lithologically. Official returns of production have come only from small mines in the Yandanooka Group in the Arrino-Yandanooka district (Table 38). Known mineralization is not impressive. It consists largely of disseminated, probably syngenetic, copper carbonates and sulphides in mafic volcanic and clastic sedimentary rocks. The mineralization has been redeposited by circulating ground waters in several cases (e.g. Arrino), but at least in the Arrino-Yandanooka area some copper may have been derived from the leaching of basement gneisses which contain rare cupriferous quartz veins.

WENMILLIA FORMATION

The Wenmillia Formation is found in a small area northwest of Mullewa, it consists of basaltic flows and sills, siltstone, shale and slate, in fault contact (Darling Fault zone) with Archaean gneiss to the east. The pelitic rocks near this contact contain a little disseminated malachite and are intruded by thin quartz veins.

BILLERANGA GROUP

The Billeranga Group crops out in a 100 km^2 area, 27 km east of Yandanooka in the Billeranga Hills. The group rests unconformably on rocks of the Yilgarn Block and is generally west-dipping. It consists of shallow-water, red-brown arenite and conglomerate, plus siltstone, dolomite, pyritic shale, quartz arenite, chert and trachytic to andesitic amygdaloidal lavas. Very minor disseminated iron and copper sulphides occur in the lavas ("Morawa Lavas"). A thin unit of chert, arenite, siltstone and carbonate rock ("Oxley Chert") contains very weak disseminations of galena, sphalerite and chalcopyrite.

YANDANOOKA GROUP

The Yandanooka Group occurs in Three Springs-Yandanooka area in an elongate synclinal tract bounded by two north-northwest-trending faults: the Darling Fault in the east and the Urella Fault in the west. In the west, the Group rests unconformably upon quartzo-feldspathic gneisses of the Mullingarra Inlier. Mature quartz sandstone, laminated red-brown to green-grey micaceous fine sandstone and siltstone, wacke,

TABLE 38. MINE PRODUCTION OF COPPER FROM THE ARRINO-YANDANOOKA DISTRICT

Mine	Copper ore and concentrates (t)	Cupreous ore and concentrates (t)	Average grade (%)	Contained copper (t)
Arrino Proprietary	38.61		20.92	8.08
Baxter	[1]600		—	—
		32.51	8.06	2.62
Mount Muggawa (Location 4441)	7.62		16.01	1.22
Sundry Claims	128.07		14.66	18.78
Totals	774.30	32.51	[2]14.84	30.70

1. Unofficial record of ore mined before 1906; copper content is unknown.
2. Average grade of copper and cupreous ore and concentrates combined, excluding the copper ore from Baxter mine.

and local developments of pebbly sandstone and conglomerate (containing clasts of intermediate volcanic rocks and/or quartz, quartzite, granitoid, gneiss and siltstone) make up the group. The basal feldspathic sandstone and pebbly sandstones contain copper mineralization in the Arrino area and east-north-east of Yandanooka. This mineralization may be derived from very low-grade syngenetic disseminated copper, relocated in fractures by groundwater movement. Disseminations and veinlets of copper minerals are also reported to occur in tuffaceous clastic rocks in the Mount Scratch area (29°21′S, 115°34′E) east of Mullingarra Hill (29°15′S, 115°31′E), and north of Mount Muggawa (ca.29°21′30″S, 115°31′E).

The old Arrino (Cyprus, Cheynes, Money Mia, Lady Bertha, Wheal Dodd) workings (29°26′30″S, 115°37′20″E) are 350 m southwest of the railway siding at Arrino, adjacent to a small creek. A group of pits and collapsed shafts can be found on the west side of the creek, and the dumps from these contain pale grey-green, medium-grained feldspathic sandstone with laminae, grain and joint coatings, and small cavity fillings of azurite and malachite. One shaft (originally 24 m deep) immediately adjacent to the creek evidently bottomed in unmineralized semi-pelitic gneiss. The first prospecting shaft was sunk in 1868 and several tonnes of ore were raised. The mineralized zone (veinlets and bunches of copper carbonates) was reported as striking at 155 degrees and dipping steeply westwards. The official production is 38.61 t of copper ore and concentrate averaging 20.92 per cent copper, raised in 1899.

The Baxter workings (29°28′40″S, 115°37′50″E) are 4.5 km at 170 degrees from Arrino, and occur in northern and southern groups about 200 m apart. The northern group was the main producing area. Copper was discovered here in 1903. Thin-bedded, pale purplish brown feldspathic sandstone strikes 010 degrees and dips at 58 degrees to the east. Over an area about 150 by 100 m (with the longest dimension parallel to the strike), numerous 1.5 m deep pits, two old shafts (flooded at 2.5 m depth) and a small open cut exposed malachite-azurite mineralization. Chalcocite was encountered at 12.5 m depth in a crosscut from one shaft. At the surface, this takes the form of networks of anastomosing millimetre-thick, vuggy quartz-malachite veinlets, and copper carbonate coated joints and bedding planes. The western limit of the mineralized area appears to be coincident with the appearance of grit and breccia composed of detritus from the underlying basement of granitoid gneiss. Outcrops of gneiss can be found about 100 m west of the shafts. At the southern group of workings, an open cut 17 m long (310 degrees), 6 to 8 m wide and 6 m deep reveals patchy malachite as joint coatings, and small irregularly stained areas adjacent to joints, fractures and quartz-limonite veinlets. A prominent joint set is oriented 295 degrees with a 45 degree southward dip. The Baxter workings were probably the major copper producer in the district, although official records only relate to 32 t of cupreous ore production for 1953 (see Table 38).

CHAPTER 19

Mullingarra Inlier

The Mullingarra Inlier is an elongate area some 70 km long and 5 km wide, of Precambrian gneissic and granitoid rocks exposed in the northern part of the Perth Basin on the Perenjori Sheet. The inlier is oriented north-northwest and is bounded by the Urella Fault to the west, and is onlapped by Proterozoic sedimentary rocks of the Yandanooka Group to the east. Phanerozoic rocks of the Perth Basin cover the inlier to the north and south.

Copper mineralization is reported 1.5 km southeast of Mount Muggawa, and between Mount Muggawa and Mount Misery to the northwest (a distance of 2.5 km). The principal workings were south-southeast of Mount Muggawa (26°22′30″S, 115°06′00″E), where a northwest-striking cupriferous zone in gneiss has been opened up over a 90 m length. Coatings of malachite and azurite occur on fracture and foliation surfaces, and more rarely disseminations and coatings are seen in small pods of vein quartz. The mineralized zone is discontinuous and less than 1 m wide. It appears to follow a 2 m wide feldspathic quartz gneiss band dipping at 45 to 65 degrees northeast, which is contained in heterogeneous quartz-muscovite-biotite-feldspar gneiss including lenses and veins of pegmatite. A few tonnes of oxidized ore may have been raised but there is no individual record of the amount.

CHAPTER 20

Albany-Fraser Province

GEOLOGY

As a whole this Province is poorly known. It covers an area of some 50 000 km^2 to the south of the Yilgarn Block. Doepel (1975) provides a comprehensive review of previous work and summarizes the major rock types as migmatite (paragneiss, orthogneiss and granitoid rocks intimately associated), and gneissic granite plus basic granulite of the Fraser Complex in the Fraser Range area (northeastern part of the province). Clearly supracrustal rocks which are involved in the province are the "Stirling-Barren Series" (Mount Barker, Bremer Bay, Newdegate and Ravensthorpe Sheets) and the Mount Ragged Beds (Malcolm Sheet). These rocks consist of quartzite, phyllite, quartz-mica schist, quartz pebble conglomerate, quartz-feldspar porphyry and rare carbonate rocks, which may contain garnet, andalusite, sillimanite, kyanite or staurolite. Variably deformed and metamorphosed mafic dykes and small syenitic intrusions (Ravensthorpe Sheet) are minor components of the province.

In the northeastern part of the province high-grade regional metamorphism, acid and basic igneous activity, and tectonism occupied the period 1300 to 1900 m.y. ago (Bunting and others, 1976). Late tectonic to post tectonic batholiths in the Albany area were emplaced in the period 1 000 to 1 200 m.y. age (Doepel, 1975, p. 98). The western boundary of the province with the Yilgarn Block is commonly transitional. The grade of metamorphism and degree of development of second foliation increases to the south or east, but the boundary may be faulted locally.

Reworked Archaean rocks have been recognized within the province, especially near its margin with the Yilgarn Block in the northeast. Metamorphosed chert, banded iron-formation and associated metasedimentary rocks in the Munglinup-Hamersley River-Naendip area have been regarded as Archaean (Sofoulis, 1958b, p. 208; Thom and others, 1977), but could equally well be younger supracrustal rocks.

In summary, the province has many features in common with other Precambrian intracratonic mobile belts, and such comparisons have been made (e.g. Wilson, 1969).

MINERALIZATION

Occurrences of cupriferous mineralization are rare and restricted to (a) the south coast south of Ravensthorpe (McCulloch prospect and Naendip mine), and (b) the Fraser Range area (Gnama South, Sixty Mile, Talbot and Yardilla South occurrences). Occurrences in the first area are cupriferous quartz veins or shears, and in the second are disseminations of iron-nickel-copper sulphides in mafic to ultramafic rocks. None is of economic importance.

SOUTH COAST AREA (TYPE C)

Information is sparse on both occurrences, and neither has been inspected. Both are near manganiferous occurrences (Sofoulis, 1958b, p. 203-212), and are associated with mica schist, metasedimentary schist, dolomite and banded iron formation which dip steeply and strike between east and east-northeast.

McCulloch (Hamersley River, Hamersley Gorge) workings (33°53′20″S, 119°53′30″E) are on the east bank of the Hamersley River, at the northern end of a series of old tenements for manganese. The occurrence was discovered in 1913 and opened up by an 11.6 m deep shaft and crosscut, and several costeans. Micaceous schist and psammite, containing lenses (up to 5 mm wide) and nodules of azurite, and veinlets of malachite and atacamite, are exposed in the workings. This mineralization is probably redeposited, supergene in origin. Small limonite-cuprite-malachite-quartz veins are also present. In 1915, 2.06 t of copper ore assaying 13.58 per cent copper (0.28 t copper) was raised.

Naendip "mine" (34°03′30″S, 119°36′20″E) is at the head of Dempster Inlet, on the north side of Coppermine Creek on Kent Location 12. The existence of copper workings here was mentioned by Blatchford (1926, p. 66) and Gray and Gleeson (1951, p. 67-68) in reports on the nearby manganese deposits, but no details are given of the copper mineralization. There is no recorded copper production.

FRASER RANGE AREA (TYPE E)

The Sixty Mile occurrence (32°03′S, 122°43′E) consists of very sparsely disseminated chalcopyrite in epidote-and hornblende-bearing migmatite in the Fraser Fault zone near the Eyre Highway (Doepel, 1973, p. 29). The Yardilla South occurrence (31°55′30″ 122°50′00″E) is similar, and consists of disseminated (to 1 per cent) pyrite and chalcopyrite in garnetiferous amphibolite in the same fault zone.

The Gnama South (32°12′S, 122°41′E) and Talbot occurrences (32°16′S, 122°43′E) are similar, and occur in small, unexposed, irregular intrusions of deformed and metamorphosed norite-pyroxenite-peridotite emplaced in the southern end of the mafic granulites of the Fraser Complex (Tyrwhitt and Orridge, 1975). 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 mineralization occurs close to norite-peridotite contacts. The best intersection obtained by Newmont in diamond drill core was from the Gnama South prospect, where a 6 m drilled width assayed 0.44 per nickel and 0.12 per cent copper. Tyrwhitt and Orridge (1975) suggested that originally syngenetic (magmatic) sulphides have been locally redistributed and concentrated during deformation.

CHAPTER 21

Remaining Phanerozoic Basins

Phanerozoic Basins remaining to be mentioned are, from north to south, as follows (with their onshore area indicated):

(a) Canning Basin—415 000 km^2

(b) Carnarvon Basin—115 000 km^2

(c) Officer Basin—390 000 km^2

(d) Perth Basin—45 000 km^2

(e) Eucla Basin—170 000 km^2

(f) Bremer Basin—12 400 km^2

Known base metal mineralization containing copper is confined to a Devonian marine shelf sequence of limestone with reefs, and to minor continental conglomerate and sandstone. This is exposed on the northeastern margin of the Canning Basin, and a similar sequence in the Bonaparte Gulf Basin also contains such mineralization (Chapter 7). The Devonian sequence present in the Carnarvon Basin is apparently unmineralized.

Other transgressive marine sequences are developed in the Middle Permian (Perth, Carnarvon and Canning Basins), Lower Jurassic (Canning Basin), Lower Cretaceous (Perth, Carnarvon, Southern Canning, and Officer Basins) and the Tertiary (Eucla and Bremer Bay Basins). However, if analogies with the sedimentary environment of important stratabound-stratiform copper deposits (e.g. Zambia-Zaïre) are sought, none of these transgressive sequences appears suitable. The combined presence of evaporites, carbonaceous shale, and arenite or dolomite, in a littoral sequence is apparently of critical importance.

Mississippi Valley type lead-zinc deposits occur at Sorby Hills and Narlarla, in Devonian carbonate rocks on the margins of the Bonaparte Gulf and Canning Basins respectively. Several authors (e.g. Dunham, 1970) have suggested that this type of deposit is formed from migrating connate metalliferous brines, which are generated from formation waters and diagenetic reactions involving black shales and carbonates or evaporites in the deep, central parts of basins or inter-reef areas. Precipitation commonly takes place at reduced load pressure and under more oxygenated conditions at around 100-140°C (from fluid inclusion studies) in structural sites (whether of sedimentary or secondary origin) on the basin margins.

Copper is not a conspicuous component in Mississippi Valley type deposits. It is virtually absent at Sorby Hills, and at Narlarla (17°15′40″S, 124°43′40″E), the main deposit (No. 2 ore body) averaged only about 0.6 per cent copper in the oxidized zone (see Blockley, 1971b, p. 107-113 and Playford, 1975, p. 535-536). If the mineralizing fluids are generated by diagenetic processes in the deeper parts of the basin, this may simply be a function of the lack of syngenetic copper in the basin sequence.

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MINERAGRAPHIC AND TRACE ELEMENT FEATURES OF SOME COPPER DEPOSITS IN WESTERN AUSTRALIA

INTRODUCTION

The mineragraphic features and mineral chemistry of selected sulphide species have been briefly examined in copper or copper-zinc deposits from the Ravensthorpe-West River area, Whim Creek, Anaconda-Nangeroo, Turtle Creek, Bunnawarra (Edamurta), Yarraloola, Freddie Well, Copper Hills, Thaduna, Wongan Hills, Narlarla, Big Stubby and Lennon Find. The most important deposits in terms of past production of copper ore are described first, followed by prospects and smaller deposits. The listed deposits are all of Type A (Chapter 3) except for Ravensthorpe—West River (modified Type ?A) and Copper Hills (Type D). *A few iron sulphides in some sedi*mentary rocks from the Archaean and Proterozoic have also been studied. Some characteristic textural features of the deposits are illustrated by Figures 50 to 53. Comparative data in the literature on the chemistry of pyrite and sphalerite has been compiled. The data is presented in Tables 39 and 40 and Figures 54 and 55. The presence of monoclinic pyrrhotite was determined using magnetic colloid solution.

The aim of this preliminary study is to give further information on the genesis of the ores, particularly with regard to the general environment of mineralization and the possible importance of post-depositional processes in reconstituting the mineralization.

RAVENSTHORPE-WEST RIVER AREA

CHALCOPYRITE

The dominant characteristic of the samples studied (from Elverdton-Mount Desmond, Mount Benson, Marion Martin, Mount Cattlin and West River) is the metamorphic recrystallization texture exhibited between xenomorphic chalcopyrite and prisms or plates of amphibole or chlorite (Fig. 50A). Chalcopyrite is commonly 0.1 to 3 mm in diameter and is present in aggregates in massive sulphides, in veinlets, and as disseminations in gangue. Some chalcopyrite tends to cluster around silicate fragments in breccia ore (Fig. 50B), and has been observed filling cracks in magnetite grains (Fig. 50C). Small inclusions of gangue minerals, pyrrhotite, pyrite and rare sphalerite are present. A symplectic intergrowth of pyrite and chalcopyrite occurred in a sample from Mount Benson. Lamellar, polysynthetic twinning in two sets was observed in many chalcopyrite grains, accompanied by broad blocky to lens-shaped ("lensatic") twins in some cases. The polysynthetic twinning is probably a response to ductile deformation of the chalcopyrite at elevated temperatures and pressures (Roscoe, 1975).

PYRITE

Much pyrite is present as clear idiomorphic individuals (up to 3 mm) and as aggregates of xenomorphic grains which occur separately from the chalcopyrite. Sieved xenomorphic crystals commonly have replacement-appearing contacts with the host rock, and pyrite may be seen mantled around silicate xenocrysts in breccia ore (Fig. 50D). Both features are suggestive of sulphide-silicate reactions. Pyrite also occurs as a filling in cracked silicates (Fig. 50E). A second variety of pyrite present in most samples is xenomorphic, clouded and contains arcuate shrinkage cracks. It is probably of supergene origin after pyrrhotite (which would account for the volume change), and occurs in otherwise unaltered primary sulphide assemblages. Small blades of marcasite may be present along grain boundaries in this supergene pyrite.

Overall, the pyrites are cobalt rich with a mean cobalt:nickel ratio of 5, but the ratio may be reversed in the case of individual deposits in the area (e.g. West River), and in the case of individual pyrite grains in a given sample (e.g. *Elverdton—Mount Desmond*). Supergene pyrite does not differ from primary pyrite in cobalt:nickel ratio.

PYRRHOTITE

Monoclinic pyrrhotite is the dominant iron sulphide in some mines. Xenomorphic grains are typically 0.1 to 1.5 mm in diameter, and have complex sutured boundaries. *Many grains contain spindle shaped defor*mation twins and are strongly to intensely kinked (Fig. 50F). By analogy with experimental studies (Clark and Kelly, 1973) these features indicate that deformation took place above 300°C. Three pyrrhotite point-analyses in a Mount Benson sample yield a mean of 45.74 atomic per cent iron and a cobalt:nickel ratio of 4.

SPHALERITE

Excepting at West River, sphalerite has only been observed as an accessory phase, commonly as small inclusions in chalcopyrite. At West River, sphalerite is xenomorphic up to 2.25 mm in diameter, and contains abundant octahedrally oriented blebs, rods or plates of exsolved chalcopyrite and pyrrhotite (Fig. 50G). Compositionally the sphalerite in both regions appears to be a low-iron variety.

OXIDES

Magnetite, ilmenite, or magnetite with lamellae of ilmenite are common minor phases. Magnetite may be a major phase occurring in foliated aggregates or disseminated porphyroblasts in the wall rocks marginal to sulphide veins. The larger grains (up to 1.5 mm) are typically cracked and more idiomorphic in outline.

ACCESSORY MINERALS

Simpson (1951, p. 63) reported cobaltite from two gold mines at Ravensthorpe and the Alice Mary copper mine at Kundip. In this study cobalt-rich bravoite has been found at West River, and a bismuth-bearing silver telluride is a rare accessory at Elverdton-Mount Desmond. Analyses of mill tailings and concentrates at Elverdton—Mount Desmond carried out by King (1966) also suggest that lead, molybdenum and selenium-bearing phases are present.

TABLE 39. TRACE ELEMENT CONTENTS IN ATOMIC PERCENT OF PYRITES FROM WESTERN AUSTRALIA

		1 Elverdton Mt Desmond	2 Marion Martin	3 Mount Benson	4 Mount Cattlin	5 West River	1 to 5 Ravensthorpe West River Area	6 Whim Creek	7 Anaconda	8 Nangeroo	9 Turtle Creek	10 Edamurta	11 Yarraloola	12 Freddie Well
Co	n	11	4	12	10	14	51	21	7	22	4	4	6	9
	$\bar{x}$	0.27	0.04	0.36	1.97	1.14	0.56	0.50	0.02	0.13	0.04	0.15	0.04	0.10
	s	0.37	0.01	0.16	1.65	0.09	0.80	0.71	0.02	0.09	0.04	0.01	0.03	0.04
	R	0.00-0.78	0.03-0.05	0.08-0.58	0.08-3.95	0.00-0.27	0.00-3.95	0.02-2.03	0.00-0.05	0.05-0.44	0.01-0.10	0.15-0.16	0.01-0.08	0.04-0.18
Ni	n	11	4	12	10	14	51	21	7	22	4	4	6	9
	$\bar{x}$	0.05	0.06	0.08	0.06	0.28	0.11	0.05	0.02	0.01	0.02	0.16	0.00	0.03
	s	0.04	0.01	0.07	0.07	0.31	0.10	0.06	0.02	0.02	0.01	0.04		0.02
	R	0.01-0.18	0.04-0.07	0.00-0.23	0.00-0.18	0.01-0.82	0.00-0.82	0.00-0.28	0.00-0.05	0.00-0.05	0.02-0.03	0.11-0.19		0.00-0.06
Cu	n		1	7	3	6		16	7	14	4	4	6	2
	$\bar{x}$		0.05	0.13	0.26	0.07		0.16	0.04	0.10	0.05	0.04	0.02	0.01
	s			0.05	0.33	0.06		0.49	0.03	0.11	0.05	0.03	0.02	0.02
	R			0.07-0.21	0.04-0.63	0.00-0.16		0.00-2.00	0.00-0.08	0.00-0.43	0.00-0.12	0.01-0.08	0.00-0.06	0.00-0.03
Zn	n			7	1	4		14	5	12	4	4	6	4
	$\bar{x}$			0.07	0.03	0.04		0.04	0.03	0.10	0.02	0.08	0.07	0.02
	s			0.05		0.05		0.03	0.03	0.12	0.03	0.06	0.06	0.01
	R			0.00-0.16		0.00-0.09		0.00-0.08	0.00-0.07	0.00-0.35	0.00-0.07	0.03-0.17	0.00-0.18	0.01-0.03
As	n	3		1				12	5	3	2		3	1
	$\bar{x}$	0.02		0.00				0.09	0.03	0.11	0.03		0.00	0.09
	s	0.02						0.07	0.04	0.07	0.05			
	R	0.00-0.03						0.01-0.26	0.00-0.10	0.04-0.17	0.00-0.07			

		13 Copper Hills	14 Wongan Hills	15 Big Stubby	16 Narlarla	17 Ilgarari	18 Beasley River	19 Mt Goldsworthy	20 Mulgine Hill	21 Lennon Find	22 Mount Palgrave	23 Mount Vernon	24A Jillawarra	24B Jillawarra
Co	n	6	6	4	1	3	3	3	3	11	14	2	4	5
	$\bar{x}$	0.06	0.08	0.16	0.02	0.07	0.17	0.04	0.02	0.09	0.07	0.09	0.07	0.08
	s	0.02	0.04	0.19		0.02	0.09	0.03	0.02	0.02	0.03	0.01	0.02	0.03
	R	0.04-0.09	0.03-0.12	0.07-0.45		0.05-0.09	0.07-0.23	0.00-0.07	0.00-0.03	0.07-0.12	0.03-0.11	0.09-0.10	0.09-0.10	0.04-0.11
Ni	n	6	6	4	1	3	3	3	3	11	14	2	4	5
	$\bar{x}$	0.00	0.02	0.04	0.01	0.01	0.36	0.09	0.01	0.05	0.21	0.24	0.00	0.13
	s		0.05	0.02		0.01	0.22	0.04	0.02	0.02	0.20	0.34		0.05
	R	0.00-0.03	0.00-0.11	0.01-0.06		0.01-0.07	0.17-0.61	0.05-0.13	0.00-0.03	0.00-0.08	0.01-0.61	0.00-0.48		0.06-0.18
Cu	n	5		4	1	2	2		3	11			4	5
	$\bar{x}$	0.04		0.04	0.03	0.00	0.00		0.04	0.08			0.10	0.06
	s	0.04		0.02					0.01	0.04			0.10	0.03
	R	0.02-0.06		0.02-0.06					0.04-0.05	0.02-0.12			0.04-0.24	0.02-0.10
Zn	n			4	1	2	3		1	11			4	5
	$\bar{x}$			0.13	0.03	0.02	0.03		0.00	0.10			0.24	0.03
	s			0.09		0.03	0.01			0.11			0.10	0.02
	R			0.01-0.20		0.00-0.04	0.02-0.04			0.00-0.27			0.12-0.34	0.00-0.06
As	n	2	5	1	1	2	1	2	2					
	$\bar{x}$	0.19	0.13	0.00	0.15	0.10	0.00	0.08	0.16					
	s	0.12	0.11			0.08		0.01	0.08					
	R	0.15-0.24	0.00-0.27			0.04-0.16		0.07-0.09	0.10-0.21					

Notes:
1. n = no. of point analyses made with electron microprobe.
2. $\bar{x}$ = arithmetic mean.
3. s = standard deviation.
4. R = range of values.
5. Absence of data indicates elements not determined.
6. See list of analysed samples for petrographic description.

TABLE 40. TRACE ELEMENT CONTENTS IN ATOMIC PER CENT OF SPHALERITES FROM WESTERN AUSTRALIA

		1 Elverdton Mt Desmond	5 West River	6 Whim Creek	7 Anaconda	8 Nangeroo	9 Turtle Creek	10 Edamurta	11 Yarraloola
Fe	n	2	8	14	1	16	3	8	2
	$\bar{x}$	3.81	4.57	3.68	3.44	5.24	5.75	6.27	3.48
	s	0.31	0.41	1.21		0.93	0.17	0.50	0.14
	R	3.59-4.03	3.92-5.20	2.32-6.05		2.64-6.18	5.57-5.89	5.78-7.30	3.38-3.58
Cu	n	2	7	13	1	16	3	6	1
	$\bar{x}$	0.81	0.18	0.35	0.49	0.57	0.09	0.67	0.13
	s	0.27	0.11	0.73		0.81	0.08	0.63	
	R	0.62-1.00	0.02-0.36	0.02-2.73		0.03-3.07	0.01-0.17	0.20-1.78	
Ni	n		3	4	1	6	3	4	1
	$\bar{x}$		0.05	0.02	0.02	0.02	0.04	0.10	0.08
	s		0.05	0.03		0.02	0.03	0.01	
	R		0.00-0.10	0.00-0.06		0.00-0.05	0.01-0.06	0.09-0.11	
Co	n		2	5	1	12	3	4	1
	$\bar{x}$		0.00	0.08	0.03	0.05	0.02	0.13	0.08
	s			0.10		0.04	0.02	0.02	
	R			0.00-0.20		0.00-0.13	0.00-0.04	0.11-0.16	
Cd	n		3	10	1	12	3	7	1
	$\bar{x}$		0.41	0.05	0.07	0.02	0.05	0.21	0.16
	s		0.05	0.04		0.02	0.03	0.09	
	R		0.35-0.44	0.00-0.12		0.00-0.08	0.03-00.8	0.13-0.37	
Zn/Fe	$\bar{x}$	11.8	9.7	12.5	13.2	8.5	7.3	6.8	13.6

		13 Copper Hills	15 Big Stubby	16 Narlarla	21 Lennon Find	22A Mount Palgrave vein	22B Mount Palgrave matrix	23 Mount Vernon	24B Jillawarra
Fe	n	2	4	1	9	3	2	2	4
	$\bar{x}$	0.70	0.50	0.45	1.08	0.04	2.58	1.58	1.00
	s	0.06	0.23		0.33	0.05	0.18	0.33	0.31
	R	0.66-0.74	0.34-0.85		0.73-1.78	0.00-0.10	2.46-2.71	1.39-1.97	0.62-1.38
Cu	n	2	4	1	9				4
	$\bar{x}$	0.70	0.24	0.65	0.07				0.79
	s	0.08	0.31		0.05				0.29
	R	0.65-0.76	0.07-0.70		0.00-0.15				0.40-1.11
Ni	n			1	1	1			
	$\bar{x}$			0.00	0.03	0.04			
	s								
	R								
Co	n		2	1	1	2			
	$\bar{x}$		0.02	0.00	0.00	0.00			
	s		0.00						
	R								
Cd	n	2	4	1	9				4
	$\bar{x}$	0.16	0.11	0.09	0.18				0.00
	s	0.01	0.02		0.02				
	R	0.15-0.17	0.09-0.13		0.14-0.23				
Zn/Fe	$\bar{x}$	69.4	99.2	106.5	49.4	1273.0	18.2	31.0	54.0

Notes:

1. n = no. of point analyses made, with electron microprobe.
2. $\bar{x}$ = arithmetic mean.
3. s = standard deviation.
4. R = range of values.
5. Absence of data indicates elements not determined.
6. See list of analysed samples for petrographic description.

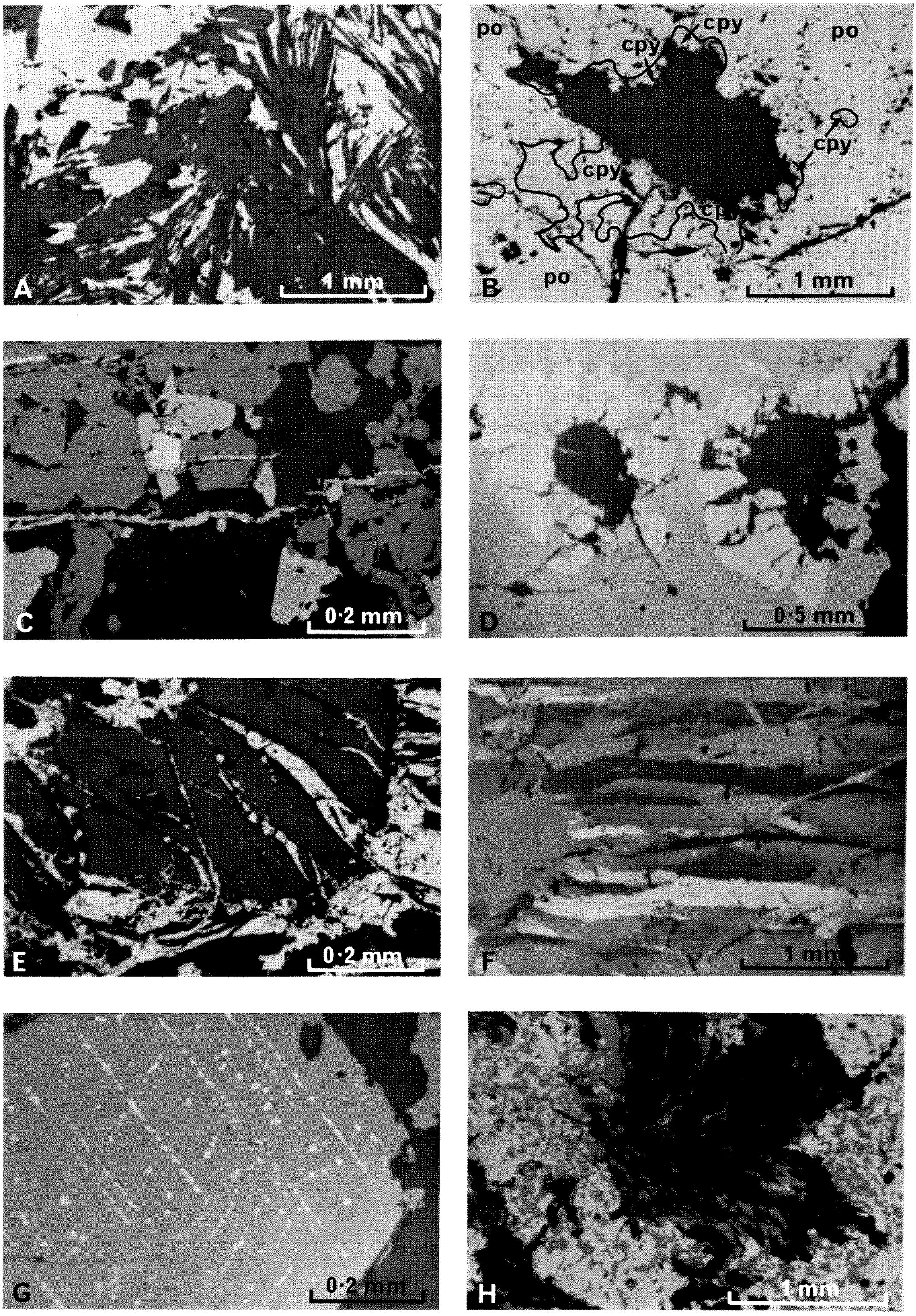

Figure 50. Photomicrographs of textures in copper deposits

WHIM CREEK

CHALCOPYRITE

Xenomorphic grains of chalcopyrite are in the size range 0.05 to 0.5 mm in diameter and contain a few lamellar and lensatic twins. Inclusions of galena and sphalerite are common. Chalcopyrite occurs in the following habits:

(a) in aggregates as a matrix to fine scale breccia ore (Fig. 50H);
(b) in the host phyllite, disseminated in layers or cross-cutting veinlets accompanied by quartz and carbonate;
(c) in massive aggregates with sphalerite;
(d) as lensoid aggregates interfoliated with silicates and carbonate (Fig. 51A);
(e) in siderite vugs; and
(f) intergrown with pyrite (Fig. 51B).

Monomineralic layering, or colloform textures, were not observed in the material examined, which was sampled from DDH 70 WCD 23 and 70 WCD 56. Replacement of chalcopyrite by digenite, chalcocite, covellite or bornite has taken place along grain boundaries and cracks in some samples (Fig. 51C). Some chalcopyrite demonstrates solid state growth textures with chlorite indicating metamorphic recrystallization.

PYRITE

Some sulphide assemblages are overwhelmingly pyritic, but in others pyrite is a minor phase to chalcopyrite and sphalerite. The habits of pyrite are as follows:

(a) as small (0.05 mm) idiomorphic grains enclosed in sulphides and silicates;
(b) forming aggregates of xenomorphic-idiomorphic grains in veinlets with carbonate;
(c) as large idiomorphs (up to 5 mm) and massive, fractured framboidal aggregates of subidiomorphic grains (1 mm) in pyritic ore (Fig. 51D);
(d) occurring as zonally grown, skeletal hopper crystals in pyritic ore (Fig. 51E), and
(e) as clouded grains, containing marcasite blades, which appear to be a supergene replacement of chalcopyrite, digenite and chalcocite.

In common with chalcopyrite and sphalerite, there are evidently several generations of pyrite formed in response to reconstitution of the ore during regional metamorphism and subsequent supergene processes.

In summary the pyrites are cobalt rich with a mean cobalt:nickel ratio of 10. Only two of the twenty one points analysed yielded a reversed cobalt:nickel ratio. Both points were on the margins of pyrite grains, several of which were found to be enriched in nickel compared with the cores. Copper is on average four times more abundant than zinc.

SPHALERITE

Sphalerite occurs in association with chalcopyrite as xenomorphic grains 0.05 to 1 mm in diameter, but is preferentially found in and marginal to gangue inclusions or host rock contacts, where solid state growth textures are exhibited between sphalerite and chlorite or carbonate (Fig. 51F). Most larger sphalerite grains contain abundant octahedrally oriented bleb—or rod-like inclusions of exsolved chalcopyrite, lesser quantities of galena inclusions, and fewer pyrite and pyrrhotite inclusions. Analysed sphalerites are low-iron varieties with a mean iron content of 3.68 atomic per cent. The iron content of sphalerites in contact with pyrite and pyrrhotite is not significantly different from that in those sphalerites in gangue, or in contact with pyrite or chalcopyrite alone. The few analyses made indicate that sphalerite is enriched in cobalt with respect to nickel, in similar fashion to pyrite.

MINOR AND ACCESSORY PHASES

Galena is present as a minor phase forming small (0.01-0.02 mm) xenomorphic to subidiomorphic grains dispersed throughout sulphides and adjacent gangue. It shows some tendency to occur marginally and as inclusions within pyrite and sphalerite. Magnetite, pyrrhotite and arsenopyrite are accessory minerals as small dispersed grains.

ANACONDA-NANGEROO

Material sampled from Anaconda mine was restricted to pyritic shale and felsic volcaniclastic rock, adjacent to the southern shoot. Except where noted, all of the following description applies to Nangeroo.

CHALCOPYRITE

Uncommonly, chalcopyrite is abundant, and occurs as aggregates of xenomorphic to polygonal grains (0.03-0.1 mm) with grain long axes parallel to a weak foliation. Pyrite and chlorite inclusions are oriented subparallel to this foliation. Polysynthetic twinning is rare, and not well developed. Solid state growth textures are present between chalcopyrite and prismatic silicates (Fig. 51G). The common habit of chalcopyrite is as inclusions in pyrite and sphalerite, as veinlets filling fractures in pyrite, and as small dispersed xenomorphic grains.

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(50) A Metamorphic recrystallization of prismatic hornblende (dark) and chalcopyrite (white). Mineralized amphibolite, Marion Martin mine, Ravensthorpe, 49019A. Plane polarized light

B Chalcopyrite grains (cpy) clustered around quartz inclusions (dark) in a massive pyrrhotite (po) matrix to breccia ore. Mount Cattlin mine, Ravensthorpe, 49043D. Plane polarized light

C Chalcopyrite veinlets (pale grey) traversing cracked aggregates of magnetite (grey) and silicates (dark grey). Magnetite-rich amphibolite and margin of sulphide-quartz vein, Mount Benson mine, Ravensthorpe, 49042B. Plane polarized light

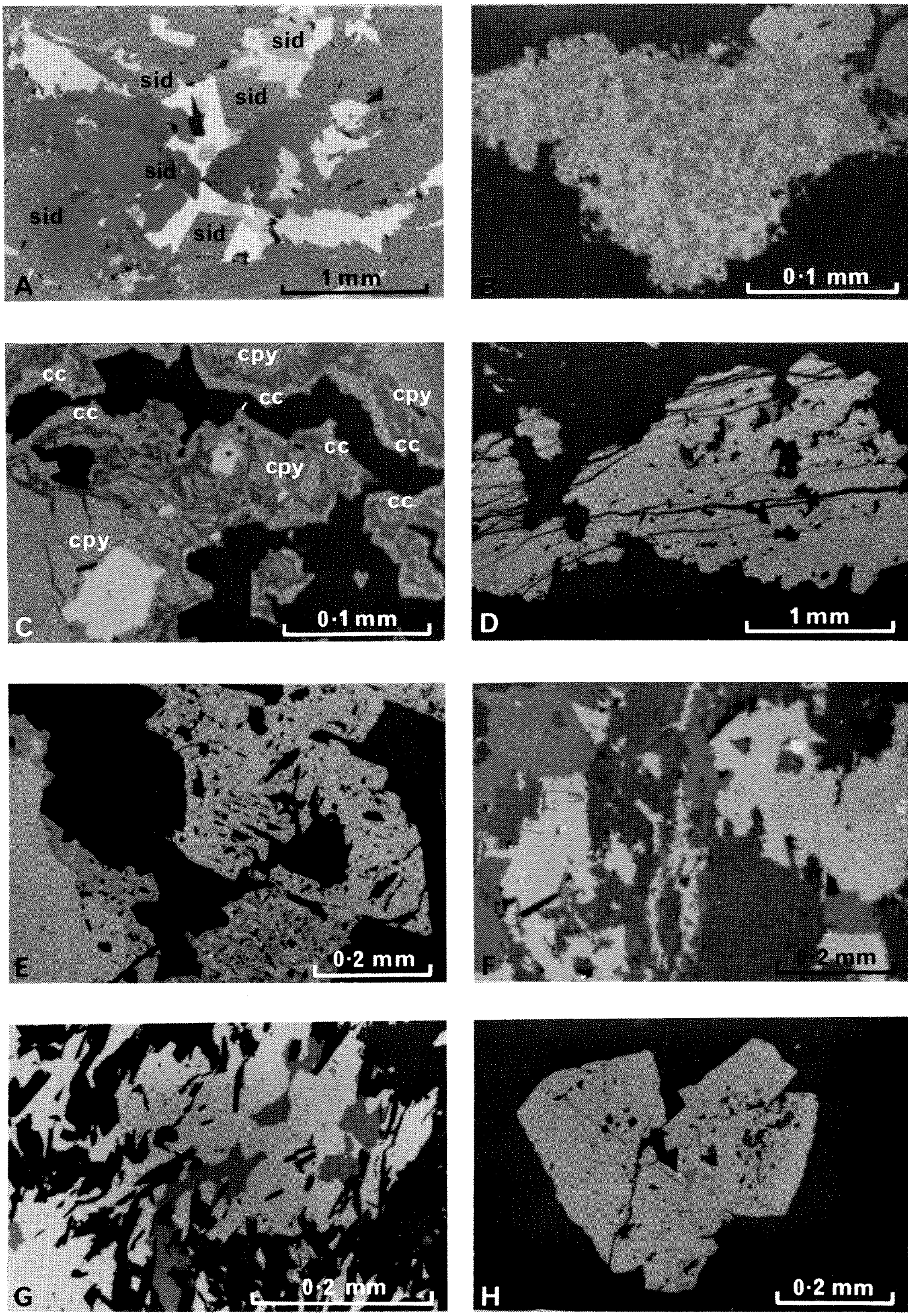
D Mantles of granular pyrite (white) around fragments of amphibole-chlorite rock (dark) in a pyrrhotite (pale grey) matrix to breccia ore. Mount Cattlin mine, Ravensthorpe, 49043C. Plane polarized light

E Pyrite (white) filling cracks in pink garnet (dark) in mineralized amphibolite. Last Venture mine, West River, 49025. Plane polarized light

F Kink bands and deformation twins in pyrrhotite matrix to breccia ore. Mount Cattlin mine, Ravensthorpe, 49043D. Analysed light

G Large sphalerite grain containing exsolved blebs and rods of chalcopyrite oriented in octahedral planes. Sphalerite-quartz vein, Copper King mine, West River, 49048. Plane polarized light.

H Deformed chlorite schist inclusion (dark) recrystallized with and mantled by sphalerite (grey), in a matrix of granular chalcopyrite (white) and lesser sphalerite. Massive breccia ore, Whim Creek mine, 49094. Plane polarized light.



GSWA 17310

Figure 51. Photomicrographs of textures in copper deposits

PYRITE

The pyrite at Anaconda is present as cracked idiomorphic to subidiomorphic grains up to 1 mm in diameter which are sieved with blebby inclusions of sphalerite, pyrrhotite, silicates and chalcopyrite (Fig. 51H). In the volcaniclastic rock from Anaconda, pyrite also occurs as veinlets, recrystallized aggregates, and laminae or trains of crystals parallel to the bedding. The mean cobalt : nickel ratio of the Anaconda pyrites analysed is unity.

The pyrite at Nangeroo is typically present as xenomorphic grains (radiating in some cases) in spherical to framboidal aggregates from 0.1 to 7 mm in diameter (Fig. 52A). Grain boundaries and fractures in the aggregates may be filled by veinlets of chalcopyrite and/or sphalerite, and pyrite-chalcopyrite intergrowths may form "atolls" around the aggregates (Fig. 52B). Pyrite also occurs as dispersed subidiomorphic to xenomorphic (more sieved with gangue inclusions) grains in gangue and massive sulphides. Locally small blades of marcasite replace pyrite. All the analysed pyrites are richer in cobalt than nickel, with a mean cobalt:nickel ratio of 13. In common with the Anaconda pyrites, copper and zinc are present in approximately equal amounts.

SPHALERITE

Grains of this mineral are generally small (0.03-0.1 mm), xenomorphic, and dispersed throughout the rock, with a tendency to cluster as larger grains around pyrite. Sphalerite contains lamellar twins and unoriented inclusions of pyrrhotite with fewer blebs of chalcopyrite and pyrite. The mean iron content is 5.24 atomic per cent, and as with pyrite cobalt is present in greater amounts than nickel. Cadmium contents are low.

ACCESSORY PHASES

Common accessories are pyrrhotite (unstrained), cassiterite and galena. Rarer minerals present are barite, gold and cobaltite. A complex suite of lead, silver and bismuth bearing selenides was found in one specimen of massive chalcopyrite-pyrite ore from Nangeroo (Fig. 52C). Two analysed species contained (a) 26 atomic per cent silver and 24 atomic per cent bismuth (argentiferous ?laitakarite), and (b) 40 atomic per cent lead and 5 atomic per cent bismuth (?clausthalite). Sphalerite and pyrite from this specimen contains trace amounts of selenium.

TURTLE CREEK (W. KIMBERLEY)

PYRITE

Alternately with pyrrhotite this mineral is the major iron sulphide present. It occurs as: (a) lensoid aggregates of xenomorphic grains up to 0.1 mm in diameter, (b) idiomorphic grains 1 to 2 mm in diameter, and (c) as clouded pseudomorphic replacements of amphibole prisms. Pyrite may occur separately from, or in solid state intergrowths with, silicates. The mean cobalt:nickel ratio of only four analyses is 2.

PYRRHOTITE

Monoclinic pyrrhotite is present as annealed, foliated aggregates of equigranular to elongate polygonal grains, containing a few flames of pentlandite (Fig. 52D). Little or no evidence of internal strain remains in most grains. Average grain diameter is about 0.1 mm, but is coarser in cross cutting veinlets, and where recrystallization has taken place along a strain slip cleavage.

LEAD-ANTIMONY SULPHOSALTS

Jamesonite and boulangerite form xenomorphic grains in coarse eutectoid intergrowths 0.5 to 1.0 mm in diameter. The jamesonite is commonly the host phase and contains two sets of lamellar to lensatic twins.

ARSENOPYRITE

This mineral forms trains of very fine-grained idiomorphs, which may replace and pseudomorph amphibole prisms in similar fashion to pyrite. Some grains are cored by pyrite. Two sets of lamellar to lensatic twins are present.

CHALCOPYRITE

Chalcopyrite is rarely a major phase; generally it occurs as sparse xenomorphs up to 0.5 mm in diameter dispersed in massive sulphides and gangue. It also constitutes a component of the coarse aggregates of sulphosalts, sphalerite and tetrahedrite. Finally chalcopyrite is found as a matrix to, and a fracture filling within, arsenopyrite.

SPHALERITE

Xenomorphs of sphalerite are up to 0.6 mm in diameter and contain bleb—and star-shaped exsolution inclusions of chalcopyrite. Three analyses gave a mean of 5.75 atomic per cent iron.

MINOR AND ACCESSORY PHASES

Tetrahedrite occurs as minute grains in, and marginal to, chalcopyrite and sphalerite. Thin cross-cutting hematite veinlets have been noted in some samples.

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(51) A Recrystallized chlorite (grey), siderite (sid) rhombs, sphalerite (pale grey) and chalcopyrite (white) in massive breccia ore. Whim Creek mine, 49094. Plane polarized light.

B Fine pyrite (pale grey) and chalcopyrite (grey) intergrowth in massive pyritic ore. Whim Creek mine, 49094. Plane polarized light.

C Supergene alteration of chalcopyrite (cpy) along grain boundaries and twin planes to digenite (grey), which is in turn rimmed by chalcocite (cc). Supergene pyrite (white) replaces all the copper sulphide phases. Foliated massive ore, Whim Creek mine, 49098.Plane polarized light.

D Cracked pyrite aggregate (light) in fragmented pyritic ore with quartz matrix (dark). Whim Creek mine, 49092. Plane polarized light.

E Skeletal pyrite crystals with chert gangue. Whim Creek mine, 49105. Plane polarized light.

F Sphalerite (pale grey with white chalcopyrite inclusions) recrystallized with siderite (grey rhombs) and chlorite. Massive breccia ore, Whim Creek mine, 49094. Plane polarized light.

G Recrystallized chalcopyrite (light), sphalerite (pale grey) and phyllosilicate (dark grey), in fragmented ore. Nangeroo mine, 49049. Plane polarized light.

H Pyrite composite grain containing inclusions of sphalerite (grey), chalcopyrite (pale grey) and silicates (dark grey). Pyritic shale, Anaconda mine, 49055. Plane polarized light.

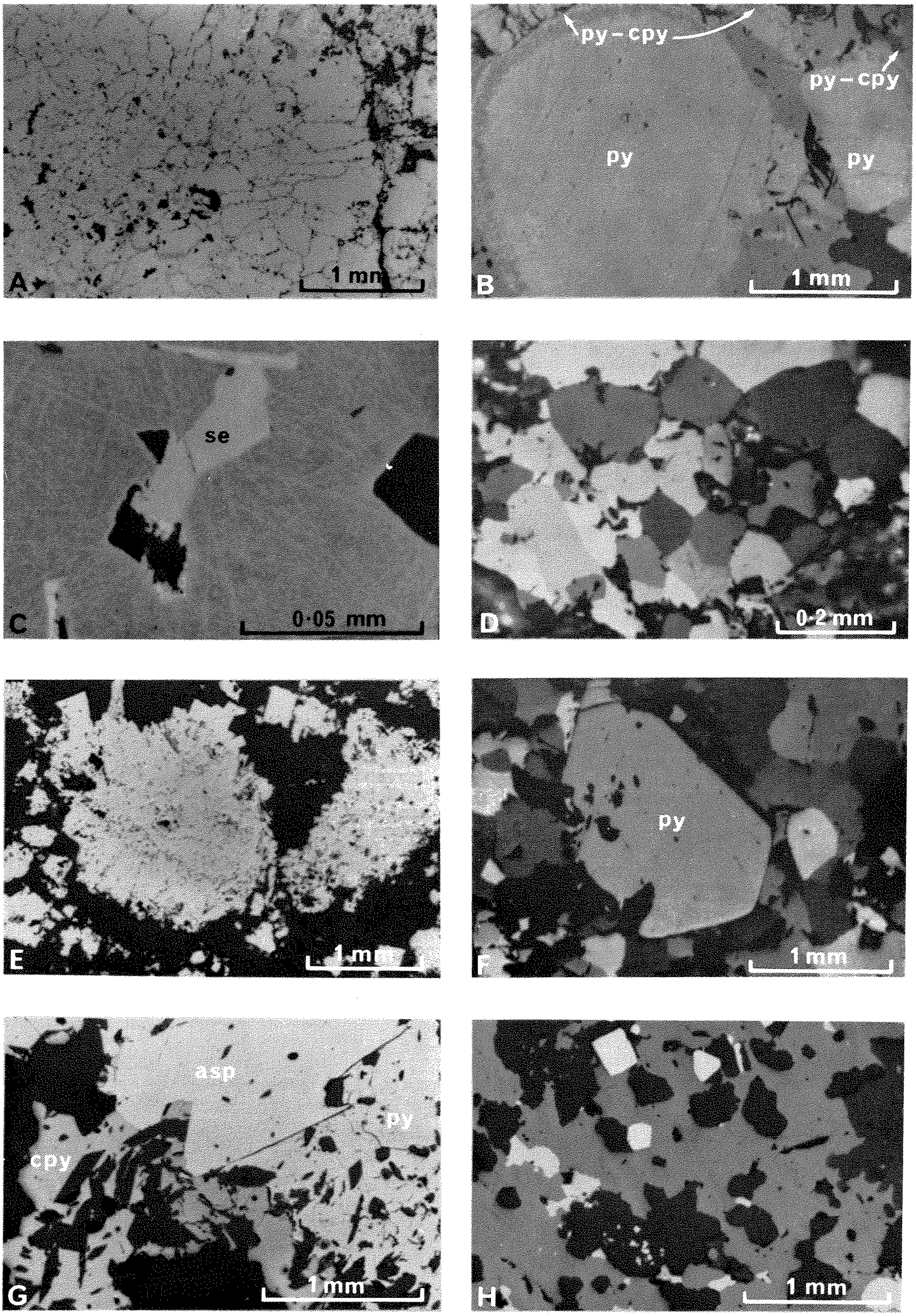

Figure 52. Photomicrographs of textures in copper deposits

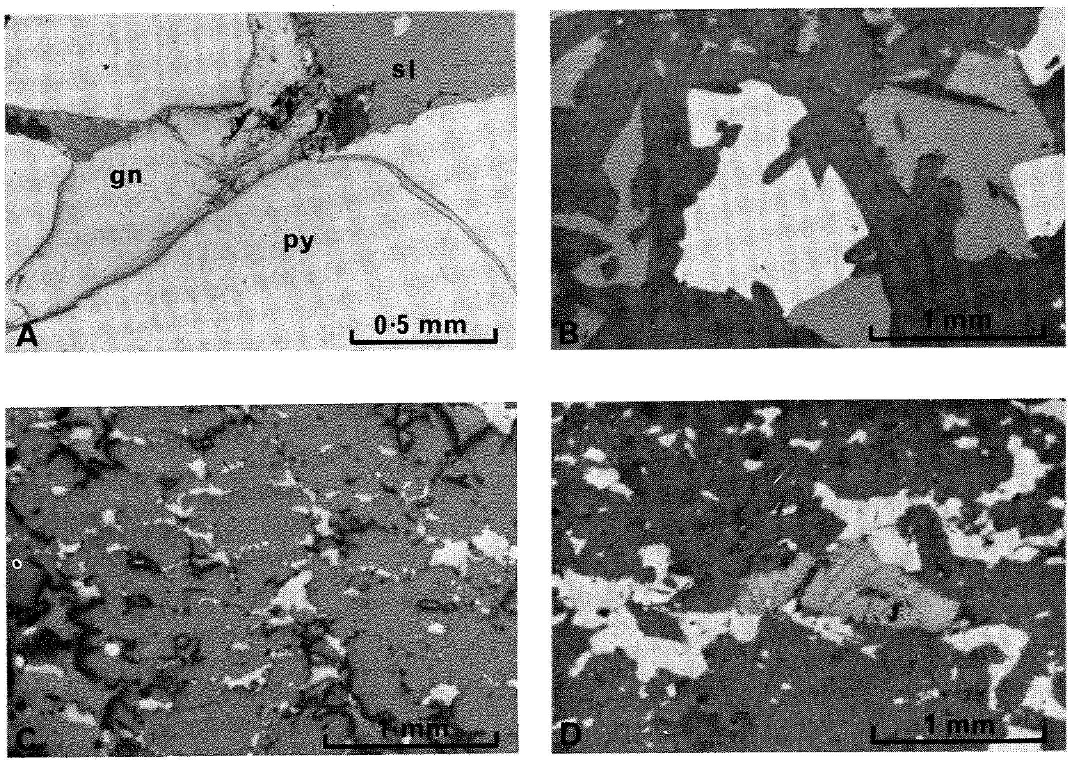

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Figure 53. Photomicrographs of textures in copper deposits

(52) A Part of a radiating spherical aggregate of pyrite with intergranular films of chalcopyrite (pale grey). Fragmented ore, Nangeroo mine, 49049. Plane polarized light.

B Fragmented atoll texture comprising a spherical pyrite (py) core and intergrown pyrite-chalcopyrite (py-cpy) margin. Massive foliated ore, Nangeroo mine, 49132. Plane polarized light.

C Composite grain of silver-bismuth and lead-bismuth selenides (se) in chalcopyrite matrix. Massive foliated ore, Nangeroo mine, 49132. Plane polarized light.

D Annealed aggregate of polygonal grains of monoclinic pyrrhotite. Massive ore, Turtle Creek prospect, 49136. Analysed light.

E Recrystallized framboidal pyrite aggregates with minute chalcopyrite inclusions (pale grey), in a quartz matrix. Yarraloola prospect, 49145. Plane polarized light.

F Large idiomorphic pyrite (py) grain enclosed by an annealed aggregate of polygonal grains of monoclinic pyrrhotite. Breccia ore, Freddie Well prospect, 49064. Analysed light.

G Large idiomorphic arsenopyrite (asp) adjacent to chalcopyrite (cpy) intergrown with amphiboles. Supergene pyrite (py) has replaced chalcopyrite on the right. Siliceous vein in schist, Wongan Hills prospect, 49163. Plane polarized light.

H Twinned sphalerite grains (pale grey) forming a matrix to quartz and carbonate grains (dark), and scattered pyrite crystals (white). Big Stubby prospect, 49118. Plane polarized light.

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(53) A Cracked pyrite grains (py) with interstitial galena (gn) and sphalerite (sl). The prominent crack is filled with galena. Tremolite needles are intergrown with galena and sphalerite. Lennon Find prospect, 44958. Plane polarized light.

B Intergrown pyrite (white), sphalerite (pale grey) and tremolite (dark grey). Lennon Find prospect, 44959. Plane polarized light.

C Elongate sphalerite grains (white) in siliceous schist. Lennon Find prospect, 44957. Plane polarized light.

D Fractured and disrupted magnetite grain (pale grey) and elongate pyrrhotite grains and aggregates (white) in siliceous schist. Bunnawarra prospect, 49084. Plane polarized light.

BUNNAWARRA (EDAMURTA)

CHALCOPYRITE

Chalcopyrite forms xenomorphic grains from 0.05 to 4 mm in diameter in (a) foliated aggregates with pyrrhotite and (b) fine disseminations in the gangue. Solid state growth textures are common with phyllosilicate phases. Large grains exhibit two sets of lensatic twins. Small inclusions of sphalerite are common.

PYRRHOTITE

Monoclinic pyrrhotite is the dominant iron sulphide as cracked xenomorphic grains containing kink bands but few deformation twins. Grain boundaries are curved, but some large grains appear to have been annealed into smaller, more polygonal subgrains.

PYRITE

Most pyrite observed is clouded, xenomorphic and probably supergene in origin after pyrrhotite. Primary pyrite is clear, tends to be more idiomorphic, and forms cracked grains up to 1.2 mm. Four analysed points give a mean cobalt:nickel ratio slightly less than unity.

SPHALERITE

Sphalerite is a minor phase in the samples examined, occurring mainly as inclusions in chalcopyrite. In turn, it contains abundant octahedrally oriented inclusions of chalcopyrite. The mean iron content of eight analysed points is 6.27 atomic per cent.

MINOR AND ACCESSORY PHASES

Magnetite and ilmenite are present as cracked subsequent porphyroblasts 0.5 to 1.5 mm in diameter. Some magnetite grains contain a few lamellae of ilmenite.

YARRALOOLA

PYRITE

This mineral is the dominant opaque phase, and occurs as (a) framboidal aggregates up to 2.5 mm in diameter of subidiomorphic grains 0.005-0.5 mm in diameter, and (b) as foliated trains of small idiomorphs scattered through the rock. Inclusions and small intergranular grains of chalcopyrite, galena, and less sphalerite are present in the aggregates, which may also exhibit marginal intergrowths with chalcopyrite and galena (Fig. 52E). Six pyrites analysed contained no detectable nickel and a mean of 0.04 atomic per cent cobalt. Zinc is a more abundant trace constituent than copper.

GALENA

Galena is generally xenomorphic, up to 1.5 mm in diameter, and is coarsely intergrown with chalcopyrite, both of which enclose small pyrite, sphalerite and quartz grains.

MINOR AND ACCESSORY PHASES

Sphalerite forms both very small and larger xenomorphs (up to 0.1 mm) associated with pyrite or galena. Chalcopyrite inclusions are present in many grains. Two point analyses yielded a mean iron content of 3.48 atomic per cent.

Chalcopyrite is generally only present in accessory amounts as separate xenomorphs or intergrown with galena.

FREDDIE WELL

PYRRHOTITE

Monoclinic pyrrhotite in breccia ore forms aggregates of annealed granuloblastic xenomorphs up to 2.5 mm in diameter, but commonly in the range 0.2-0.5 mm (Fig. 52F). The grains are polygonal without any obvious elongation excepting those disseminated in schistose rocks, which have a lensoid shape. Annealing may have removed evidence of strong deformation as the grains are now only weakly twinned, and weakly to moderately kinked. Two analysed crystals contain 47.0 atomic per cent iron.

PYRITE

Present in roughly equal proportions to pyrrhotite, pyrite occurs as idiomorphic crystals up to 2.5 mm in diameter, and in cracked aggregates several millimetres across. The cracks may be filled by chalcopyrite veinlets. Oriented inclusions of gangue indicate solid state growth of some pyrites, and the clustering of some pyrite grains around large quartz fragments is suggestive of nucleation. All pyrite analysed is enriched in cobalt with a mean cobalt:nickel ratio of 3.3.

MINOR AND ACCESSORY PHASES

Magnetite occurs as cracked and sieved porphyroblasts up to 1 mm in diameter, and ilmenite is present as smaller dispersed xenomorphs.

Chalcopyrite forms sparse, small xenomorphs and fills fractures in quartz and pyrite. Sphalerite was not present in the samples examined.

COPPER HILLS

Pyrite is the major opaque phase, and it forms idiomorphic to subidiomorphic crystals 0.1 to 0.8 mm in diameter dispersed through the porphyry host rock, or in sparse aggregates. Tiny blebby inclusions of chalcopyrite and pyrrhotite are rare. Only one of the six pyrites analysed contained detectable nickel: the mean cobalt content is 0.06 atomic per cent.

Chalcopyrite and magnetite are minor to accessory phases. Sphalerite is a sparse accessory, and two analyses gave a mean iron content of only 0.70 atomic per cent. Besides containing small blebs of chalcopyrite, substantial trace amounts of copper are also present in the analysed sphalerite.

WONGAN HILLS

Xenomorphic chalcopyrite intergrown (recrystallized) with silicates is the major phase as disseminations in the country rocks, but the major sulphide phases in the small siliceous veins and veinlets examined are pyrite and arsenopyrite. Arsenopyrite forms idiomorphic grains up to 2.5 mm in diameter, accompanied by clear idiomorphic pyrite up to 2 mm which contains chalcopyrite and silicate inclusions (Fig. 52G). Clouded supergene pyrite with curved shrinkage cracks is also present and may be after pyrrhotite and chalcopyrite. Nickel was detected in only one pyrite, the mean cobalt : nickel ratio being 4.

BIG STUBBY

In the sample examined, sphalerite forms a massive matrix to chalcopyrite, pyrite, quartz and carbonate (Fig. 52H). The sphalerite is xenomorphic, 0.2 to 0.3 mm in diameter and contains lamellar twins. Subspherical chalcopyrite blebs occur sparsely as inclusions. The iron content of the sphalerite is very low with a mean of 0.50 atomic per cent. Chalcopyrite is present as xenomorphic grains 0.1 to 0.8 mm in diameter, containing a few lensatic twins and exhibiting marginal and spotty alteration to digenite. Pyrite is subidiomorphic to 1 mm in diameter and contains many sphalerite inclusions and fewer chalcopyrite and galena inclusions. Compositionally the pyrite is cobalt rich with a cobalt : nickel ratio averaging 4, and it contains a mean of 0.13 atomic per cent zinc.

LENNON FIND

PYRITE

In the massive sulphides examined pyrite is idiomorphic to subidiomorphic and generally coarse grained, ranging in diameter from 0.1 to 3.0 mm, but where disseminated in schist the grain size is 0.05 to 0.5 mm. Most grains are clear and free of inclusions, but a few large inclusions of chalcopyrite, sphalerite and galena may be present. Galena, and lesser amounts of chalcopyrite and sphalerite occur in cracks and along grain boundaries in pyrite aggregates (Fig. 53A). Solid state growth textures occur between amphibole, pyrite and sphalerite (Fib. 53B). Without exception the analysed pyrites are enriched in cobalt, with a mean cobalt : nickel ratio of 1.8. Zinc is present in slightly greater amounts than copper, even though the bulk sulphides are very poor in copper relative to zinc.

SPHALERITE

Sphalerite may be the dominant sulphide phase. In massive sulphides it forms xenomorphic grains 0.1 to 2.5 mm in diameter, which exhibit abundant coarse polysynthetic twins. Where present inclusions are of chalcopyrite (up to 0.07 mm), and fewer small cuspate galena grains. The inclusions are both irregularly and octahedrally distributed within the sphalerite. Sphalerite is also present as lensoid xenomorphs (0.1 to 0.7 mm in length) aligned in the foliation of enclosing siliceous schist (Fig. 53C). The mean iron content of nine analyses is 1.08 atomic per cent.

GALENA

This mineral is generally a minor phase concentrated as: (a) small cuspate grains along sulphide-sulphide and sulphide-silicate grain boundaries, (b) replacement xenomorphic grains in the siliceous host rock, and (c) in small aggregates exhibiting solid state growth textures with radiating tremolite needles (Fig. 53A).

CHALCOPYRITE

Chalcopyrite is a minor to accessory mineral, present largely as inclusions in sphalerite, but also as tiny grains in the gangue and locally in clusters with galena along sulphide-silicate contacts.

MOUNT PALGRAVE

The Mount Palgrave prospect (23°22′S, 115°58′E) is in the Jillawarra Formation of the Bangemall Group, in the western part of the Proterozoic Bangemall Basin. The samples examined are black, silty pyritic shales, some of which contain an incipient strain-slip cleavage.

PYRITE

Pyrite is disseminated throughout all samples as subididiomorphic grains 0.01 mm in diameter. Larger crystals up to 2.5 mm occur as separate cubes and cracked aggregates forming small nodules or concordant lenses up to 5 mm thick. Inclusions of chalcopyrite and sphalerite occur in some but not all the larger grains, and are generally lacking in the small, dispersed grains of pyrite. The mean cobalt:nickel ratio of all analysed pyrite is 0.33. The only cobalt-rich pyrites are idiomorphs occurring in or adjacent to a cross-cutting iron-free sphalerite-pyrite veinlet in *sample 42686. This pyrite is apparently of a later generation* than that pyrite (all nickel rich) which is disseminated in the matrix, in nodules, or concordant lenses.

SPHALERITE

As with pyrite, there are also two generations of sphalerite. Low-iron sphalerite (about 2.5 atomic per cent iron) occurs as inclusions in pyrite, and rare small grains in the matrix which tend to cluster near large pyrites. Iron-free, pale-brown sphalerite is present in much greater quantity, but appears to be confined to cross-cutting veinlets.

CHALCOPYRITE

Chalcopyrite is an accessory phase included in pyrite. It is partly altered to bornite.

MOUNT VERNON

The Mount Vernon prospect (24°18′S, 119°08′E) is in the Glen Ross Shale Member of the Bangemall Group, in the central part of the Bangemall Basin. The samples examined are black, silty pyritic shales, with a less well developed fissility compared to the Mount Palgrave locality.

PYRITE

Pyrite is disseminated through the rock as minute subidiomorphs less than 0.01 mm in diameter. Larger grains are up to 0.05 to 0.1 mm in diameter containing chalcopyrite and sphalerite inclusions, and pseudomorphic grains up to 0.4 mm occur replacing layered silicate minerals. Nickel-rich and nickel-poor types appear to be present.

SPHALERITE

Sphalerite is far less abundant than pyrite, being present as (a) scattered, ragged xenomorphs of similar size range to pyrite, and (b) lensoid grains up to 0.4 mm long intergrown with a silicate phase. Tiny filamentous inclusions of chalcopyrite or covellite occur in the larger sphalerite grains. Two analysed points average 1.58 atomic per cent iron, which is comparable with the matrix sphalerite at Mount Palgrave.

JILLAWARRA

The Jillawarra Prospect (24°40′S, 118°24′E) is in the central part of the Bangemall Basin. One sample (48507) is a silty shale of the Devil Creek Formation

(Bangemall Group) containing disseminated fine-grained pyrite and rare sphalerite. A second sample (48566) consists of subidiomorphic pyrite (up to 1 mm) in aggregates set in a matrix of sphalerite and galena. This mineralization is near a fault zone involving the Discovery Chert (Bangemall Group). Geochemically the pyrites from these two samples are different. The pyrite from the silty shale is nickel rich with a mean cobalt:nickel ratio of 0.6, whereas the pyrite in massive sulphide is cobalt rich with a mean cobalt content of 0.07 atomic per cent and a lack of detectable nickel. The copper and zinc contents of the massive sulphide pyrite are greater than those of the silty shale pyrite, and zinc is more abundant than copper, whereas the reverse is true for the silty shale pyrite.

DISCUSSION

The host rocks of almost all the sulphide assemblages studied have been converted to metamorphic mineral assemblages equilibrated under varying temperatures and pressures, equivalent to conditions ranging from the prehnite-pumpellyite (e.g. Nangeroo, Ilgarari, Mount Vernon) to the amphibolite facies (e.g. Ravensthorpe, Bunnawarra, Wongan Hills). There is abundant textural evidence that the sulphide phases have also suffered such metamorphism. Solid state intergrowth (i.e. recrystallization) textures between sulphides and metamorphic minerals such as hornblende, tremolite and chlorite, are widespread at all metamorphic grades (Figs. 50A, 50H, 51A, 51G, 52G, 53A and 53B). Excluding pyrite, the maximum grain size of sulphide phases tends to increase with increasing metamorphic grade. For example chalcopyrite and sphalerite grain diameters increase from 0.1 to 1.0 and finally to 3.0 mm, in the series of deposits: Nangeroo—Whim Creek—Ravensthorpe (West River). This is paralleled by increases in the grain size of metamorphic silicate minerals.

With increasing metamorphic grade (which is commonly accompanied by stronger deformation) there is a tendency for the low-strength sulphide minerals (pyrrhotite, chalcopyrite, sphalerite) to become elongated within the metamorphic foliation, particularly where the sulphides are disseminated (Figs. 53C, 53D). This of course is another feature shared by the silicate minerals. The effect of deformation during regional metamorphism on sulphides and oxides, whether disseminated or massive, varies considerably with the internal structure of the mineral (which governs the nature of the deformation process), and is critically dependent on how the strength of that mineral varies with pressure and temperature. This has been established by experimental studies (see summary in Mookherjee, 1976, p. 220-221), though the much slower strain rates obtaining in nature would result in lower mineral strengths and more widespread ductile behaviour than found in laboratory studies.

Of the common opaque minerals in the rocks studied, pyrite and magnetite are the strongest and galena the weakest at all temperatures, whereas the behaviour of chalcopyrite, sphalerite and pyrrhotite though intermediate in character is very temperature dependent (cf. Kelly and Clark, 1975, p. 451). Textural features faithfully reflect these properties. Early generations of pyrite and magnetite are commonly cracked and (along with some silicates) the fractures or grain boundaries are filled with ductile minerals such as chalcopyrite (Fig. 50C) and galena (Fig. 53A). Pyrrhotite has deformed in a ductile fashion compared with magnetite (Fig. 53D) or pyrite, and in higher grade metamorphic environments contains abundant spindle-shaped deformation twins (Fig. 50F), a feature which is compatible with the results of experimental runs above 300°C (Clark and Kelly, 1973). Polysynthetic twinning in chalcopyrite (e.g. as present at Ravensthorpe) is probably a deformation feature, which has been reproduced experimentally above 100°C at 500 bars (Kelly and Clark, 1975). In sphalerite polysynthetic twinning (observable without etching) is of a coarser type than that ascribed to deformation twinning, but the common occurrence of octahedrally oriented chalcopyrite inclusions in sphalerites from more metamorphosed environments (e.g. West River, Edamurta, Whim Creek) suggests that strain-induced exsolution has taken place along slip planes.

Physical migration of softer minerals may also account for chalcopyrite (Fig. 50B) or sphalerite (Fig. 50H) mantles around deformed host rock fragments in breccia ore. The actual generation of breccia ore, consisting of deformed silicate crystal or rock fragments in a matrix of massive sulphides is probably largely contingent upon the existence of ductile sulphides such as pyrrhotite, sphalerite, chalcopyrite and galena (e.g. Ravensthorpe, Freddie Well, Big Stubby). Though obscured by recrystallization, a textural phenomenon of similar origin in gangue-free massive sulphides, may be the presence of aggregates of large pyrite grains in a matrix of galena, sphalerite or pyrrhotite (e.g. Jillawarra, Lennon Find, Yarraloola and Turtle Creek).

Figure 54. Nickel and cobalt contents of pyrites from copper deposits and rocks in Western Australia, Tasmania, North Africa, Cyprus and South Africa

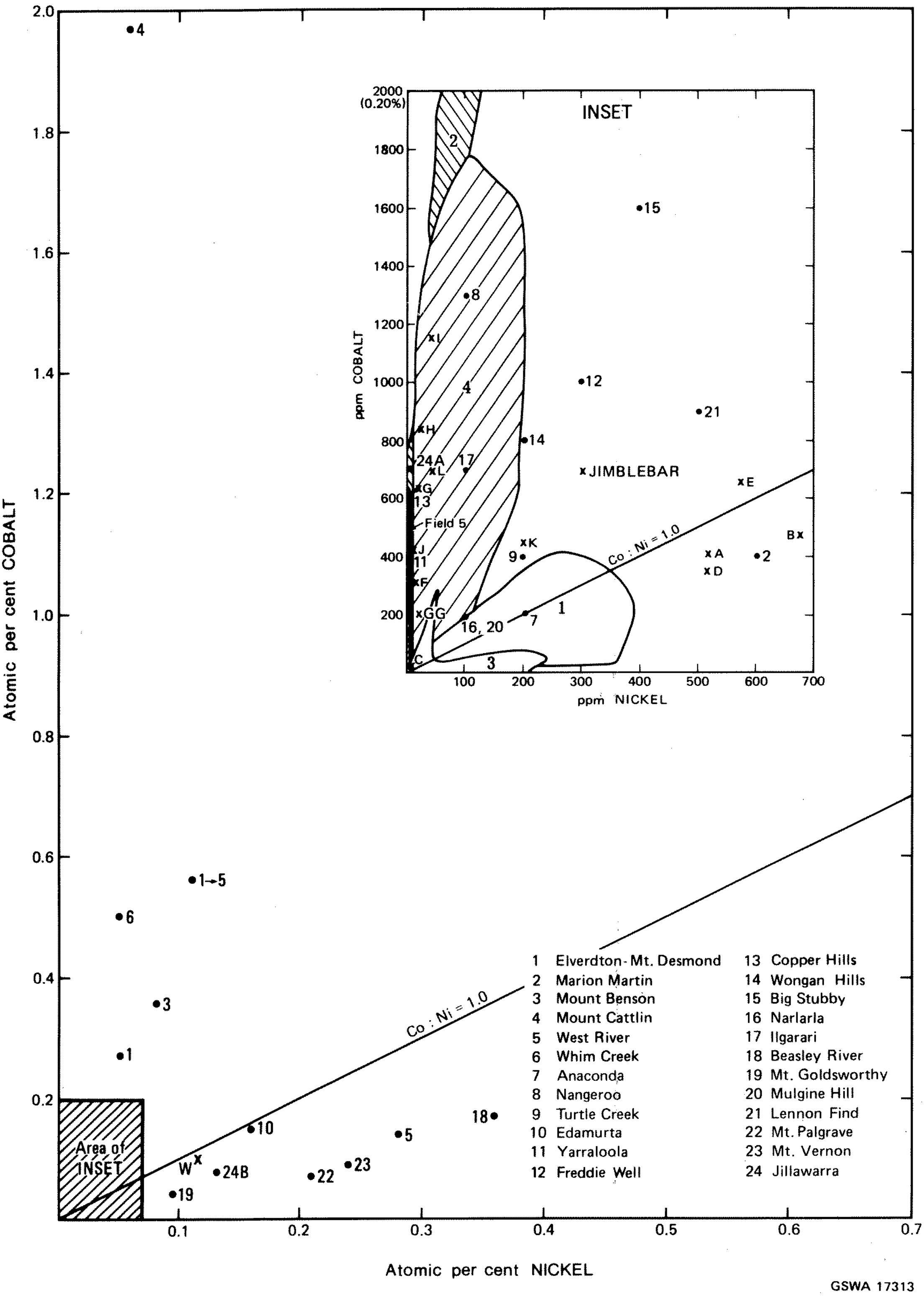
(a) Source of Western Australian data obtained in this study is indicated on the face of the figure.

(b) *Other Australian data are as follows—*

- i Numbered fields on INSET are taken from Groves and Loftus Hills (1968):
  - 1 sedimentary pyrites
  - 2 pyrites in Mount Read Volcanics and related Cambrian intrusive rocks
  - 3 *pyrites in Devonian granitoids and tin-sulphide, lead-zinc-silver ores*
  - 4 pyrites in Mount Lyell ores
  - 5 pyrites in Rosebery-Hercules ores
- ii A=pyrite in host shales at Rosebery mine (Loftus Hills and Solomon, 1967)
- iii *GG=pyrite in Golden Grove deposit (Rutter, 1973)*

Other world data are as follows—

- B = pyrite in host metasediments, Balmat (Doe, 1962)
- C = pyrite in iron-zinc-lead ore, Balmat (Doe, 1962)
- D = pyrite in Archaean gold-quartz veins, S. Africa (Saager, 1976)
- E = pyrite in iron-copper-zinc-gold ore, Flin Flon (Hawley and Nichol, 1961)
- F = pyrite in iron-copper-zinc ore, Geco (Hawley and Nichol, 1961)
- G = pyrite in iron-copper-zinc ore, Normetal (Hawley and Nichol, 1961)
- H = pyrite in iron-copper-zinc ore, Quemont (Hawley and Nichol, 1961)
- I = pyrite in iron-copper-zinc ore, Horne (Hawley and Nichol, 1961)
- J = pyrite in massive iron-copper ore, Cyprus (Mercer, 1976)
- K = pyrite in stockwork iron-copper ore, Cyprus (Mercer, 1976)
- L = pyrite in massive iron-copper-lead ore, Bathurst (Mercer, 1976)
- W = Witwatersrand, 8 syngenetic pyrites (Saager, 1976)



INSET
2000 (0.20%)
1800
1600
1400
1200
1000
800
600
400
200
ppm COBALT
100
200
300
400
500
600
700
ppm NICKEL
Field 5
JIMBLEBAR
Co : Ni = 1.0
Area of INSET
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
Atomic per cent COBALT
0.1
0.2
0.3
0.4
0.5
0.6
0.7
Atomic per cent NICKEL
1→5
24B
1 Elverdton-Mt. Desmond
2 Marion Martin
3 Mount Benson
4 Mount Cattlin
5 West River
6 Whim Creek
7 Anaconda
8 Nangeroo
9 Turtle Creek
10 Edamurta
11 Yarraloola
12 Freddie Well
13 Copper Hills
14 Wongan Hills
15 Big Stubby
16 Narlarla
17 Ilgarari
18 Beasley River
19 Mt. Goldsworthy
20 Mulgine Hill
21 Lennon Find
22 Mt. Palgrave
23 Mt. Vernon
24 Jillawarra
GSWA 17313

Following metamorphism and deformation, textural and mineralogical changes take place in sulphides in ways partly analogous to the recovery and annealing of metals. Pyrrhotite aggregates show annealed textures, with polygonal grains and many triple point contacts, and the partial erasure of internal strain (kink bands, deformation twins), in samples from Turtle Creek and Freddie Well (Figs. 52D, 52F). The lamellar twinning present in sphalerites from more metamorphosed environments may be developed in response to annealing. Falling temperatures promote immiscibility and resulting exsolution of chalcopyrite from sphalerite. Symplectic pyrite-chalcopyrite intergrowths (e.g. Ravensthorpe) may be the result of unmixing of intermediate solid solution in the Cu-Fe-S system at low temperatures. In the presence of pyrite, hexagonal pyrrhotite inverts to monoclinic pyrrhotite below about 250°C, which is not surprisingly the common phase present in the material examined.

It can be argued that "the strain energy stored in the dislocated array of the deformed matrix is a sufficient motivating force for annealing recrystallization" (Mookherjee, 1976, p. 225). However the common occurrence of randomly oriented or "static" recrystallization textures between silicates and sulphides (which are analogous to the presence of static growths of amphiboles or chlorites superimposed on the metamorphic foliation in the enclosing country rocks), and of idiomorphic pyrite grains and porphyroblasts indicate another driving force. This is proposed to be either thermal metamorphism that outlasted deformation, or a subsequent metamorphic event that followed regional metamorphism.

The textural evidence thus points to the described sulphide assemblages being pre-metamorphic components of their host rocks. The data on mineral chemistry may help define the nature of the environment of mineralization, if there has not been major redistribution of the elements concerned during regional metamorphism. Opinion is divided on how reliable cobalt:nickel ratios of pyrite are in indicating conditions of genesis (e.g. Loftus-Hills and Solomon, 1967) versus conditions of metamorphism (e.g. Rickard and Zweifel, 1975). An increase in the cobalt:nickel ratio in pyrite from unmetamorphosed to upper greenschist facies environments has been documented by Ito, (1971), as quoted in Mookerjee (1976, p. 215). However, geochemical contrasts between cobalt-rich pyrites in massive, stratabound iron-copper-lead-zinc sulphides, and nickel-rich pyrites in adjacent sedimentary country rocks seem to be equally well preserved in very low-grade (e.g. Lambert and Scott, 1973) and low to medium-grade metamorphic environments (e.g. Doe, 1962; Loftus-Hills and Solomon, 1967). Host rocks in contact with massive sulphide bodies may show depletion in nickel and enrichment in cobalt (Fryer and Hutchinson, 1976). This effect would probably be reflected in the composition of pyrites in such rocks.

The Western Australian data on cobalt and nickel contents of pyrite (Table 39; Fig. 54) is in good agreement with the Tasmanian data of Loftus-Hills and Solomon (1967), and Groves and Loftus-Hills (1968). Stratabound copper-zinc deposits in Western Australia, which from geological evidence are hosted by rocks of *undoubted* volcano-sedimentary origin (Whim Creek, Nangeroo, Golden Grove, Big Stubby) contain cobalt-rich pyrites, which plot in or near the fields of pyrites in Mount Lyell ores and pyrites in the Mount Read Volcanics and related Cambrian intrusive rocks. Pyrite from the Mons Cupri deposit contains 75 to 4 580 ppm cobalt and averages 500 to 600 ppm (G. C. Sylvester, pers. comm. 1977). Stratabound deposits enclosed in medium- to high-grade metamorphic rocks *probably* of volcano-sedimentary origin (West River, Turtle Creek, Bunnawarra, Yarraloola, Freddie Well, Jimblebar and Wongan Hills) also contain cobalt-rich pyrites with the exception of West River and Edamurta. A sample from the Copper King locality at West River does contain cobalt-rich pyrite, which in the mean is offset by nickel-rich pyrite from another locality in a sample containing bravoite. The pyrites in the Ravensthorpe area copper deposits, though now largely occurring in metamorphosed fissure fillings associated with hydrothermal quartz, clearly indicate a volcanic affiliation for the deposits, which seem in general to be part of an exceptionally cobalt-rich province. The felsic volcanic environment of the mineralized porphyry at Copper Hills appears to be reflected in the cobalt-rich nature of the pyrite.

Disseminated pyrite in sedimentary rocks from the State (Anaconda, Ilgarari, Beasley River, Mount Goldsworthy, Mount Palgrave, Mount Vernon and Jillawarra) is nickel rich with the unexplained exception of a siltstone sample from Ilgarari. In general, the proportion of copper to zinc in all pyrites is a reflection of the proportions of copper versus zinc sulphides in the mineralization (Table 39).

The iron contents of the sphalerites examined (Table 40, Fig. 55) range from zero (veinlet at Mount Palgrave) to a high of 7.3 atomic per cent (Bunnawarra). Scott (1976) has shown that the iron contents of sphalerite that has recrystallized in equilibrium with pyrite and hexagonal pyrrhotite above about 250-300°C, is dependent on pressure alone (except at very high temperatures). None of the samples examined appear to meet the qualifying conditions, probably because of a lack of initial equilibration, and/or because of retrograde re-equilibration (cf. Groves and others, 1975). The only general (and unexplained) feature to emerge is that sphalerites in deposits from the Pilbara Block (excepting Jimblebar) have lower iron contents than their counterparts from the Yilgarn Block (Fig. 55). Copper is present in solid solution in amounts up to 3.07 atomic per cent.

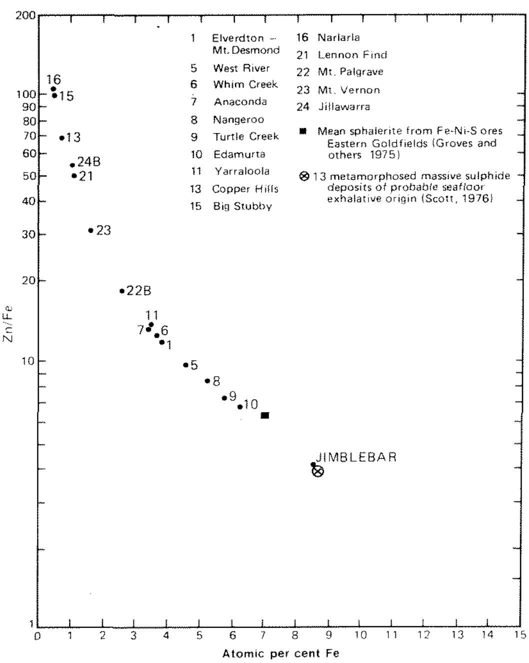


Figure 55. Iron contents of sphalerites from copper deposits and rocks in Western Australia

The mean cadmium contents of analysed sphalerites range from zero to 0.41 atomic per cent, with most values being between 0.02 and 0.21 atomic per cent (Table 40). With the exception of Narlarla all the samples giving means in the 0.02 to 0.21 atomic per cent cadmium range (overall mean 0.11 atomic per cent) are from environments of volcanic affiliation on the basis of geology and/or the presence of cobalt-rich pyrite. Groves and Loftus-Hills (1968) found that the cadmium contents of sphalerites in banded iron-lead-zinc deposits at Rosebery-Hercules (range 0.04-0.09, mean 0.07 atomic per cent), and iron-copper ores at Mount Lyell (range 0.08-0.13, mean 0.11 atomic per cent), were lower than those of sphalerites in cassiterite-sulphide deposits (range 0.09-0.15, mean 0.12 atomic per cent) and lead-zinc-silver fissure deposits (range 0.004-0.26, mean 0.14 atomic per cent). In the light of this data, and evidence compiled by Ivanov (1964) indicating that sphalerites from lead-copper-zinc and iron-lead-zinc ores in extrusive rocks commonly have lower than average cadmium contents (mean values of 0.05 to 0.13 atomic per cent), Groves and Loftus-Hills (1968, p. 49) concluded that the low Tasmanian values point to a genetic association between ore deposition and vulcanism. A more recent data compilation by Mercer (1976) tends to confirm this pattern. Although the Western Australian data is very preliminary and does not draw upon sufficient comparative data from fissure or hydrothermal deposits, the values obtained seem to be consistent with those of ores of volcanic affiliation.

CONCLUSIONS

1. Most, if not all, textural features in the deposits owe their origin to the deformation and metamorphism, which has also affected their host and country rocks.
2. The cobalt and nickel contents of pyrites in the deposits described are useful indicators of genesis, especially where geological features diagnostic of the environment of mineralization are obscured by deformation and/or metamorphism.
3. The cadmium content of sphalerite is indicated to have some potential as a genetic discriminator between environments of mineralization.

LIST AND DESCRIPTION OF ANALYSED SAMPLES

1. ELVERDTON-MOUNT DESMOND MINE
   - 49001 plagioclase-quartz-hornblende-magnetite rock with pyrite-chalcopyrite vein (underground drill core).
   - 49002 heavy disseminated chalcopyrite-pyrite, quartz gangue (underground drill core).
2. MARION MARTIN MINE
   - 49019A amphibolite, statically recrystallized, with chalcopyrite-pyrite patches (surface drill core).
3. MOUNT BENSON AREA
   - 49035 chalcopyrite-quartz vein in porphyritic metadacite (drill core RN 103, 283 ft.)
   - 49042B massive chalcopyrite-pyrrhotite microbreccia and magnetite-rich wall rock (drill core, RN 102, 469 ft.)
4. MOUNT CATTLIN MINE
   - 49043A foliated chalcopyrite-pyrite with quartz fragments (ore bin)
   - 49043C massive pyrrhotite-chalcopyrite and amphibole-chlorite rock (ore bin).
5. WEST RIVER AREA
   - 49045 biotite-amphibole-chalcopyrite-pyrite rock (Anomaly A, drill core, WRD 5, 37.1 m)
   - 49048 sphalerite-quartz vein (Copper King, drill core, WRD 7, 105.7 m)
6. WHIM CREEK MINE
   - 49092 disseminated coarse pyrite-chalcopyrite in chert (drill core, WCD 23, 113 ft.)
   - 49094 chalcopyrite-rich silicate microbreccia (drill core, WCD 23, 116.5 ft.)
   - 49095 massive fractured pyrite (drill core, WCD 23, 118.5 ft.)
   - 49104 massive chalcopyrite-sphalerite (drill core, WCD 56, 232 ft.)
   - 49105 massive pyrite with chert (drill core, WCD 56, 234 ft.)
7. ANACONDA MINE
   - 49055 pyritic black shale (dump adjacent southern open cut)
   - 49056 fine volcaniclastic breccia with pyrite (dump adjacent southern open cut)
8. NANGEROO MINE
   - 49049 pyritic meta-rhyodacitic breccia (drill core WMM 7, 364.5 ft.)
   - 49059A massive coarse pyrite, fine sphalerite rock (dump)
   - 49059B foliated fine-grained pyrite-sphalerite rock (dump)
   - 49132 foliated fine-grained chalcopyrite-pyrite (drill core, WMM 11, 379.5 ft.)
9. TURTLE CREEK PROSPECT
   - 49134 pyritic hanging-wall phyllite (drill core, RDH 2, 101.6 m)
   - 49136 foliated pyrrhotite plus pyrite, chalcopyrite, sphalerite and arsenopyrite (drill core, RDH 2, 104.12 m)
10. BUNNAWARRA (EDAMURTA) PROSPECT
    - 49077 chlorite-quartz-garnet schist with chalcopyrite and pyrite patches (drill core, DDH 8, 109.8 m)
    - 49083 interfoliated chlorite-sericite-tremolite-biotite and chalcopyrite-pyrrhotite (drill core, DDH 8, 191 m)
11. YARRALOOLA PROSPECT
    - 49142 foliated pyrite and quartz aggregates (drill core, YD 2, 262 ft.)
    - 49145 foliated pyrite-galena-sphalerite-chalcopyrite with quartz (drill core, YD 6, 514 ft.)
12. FREDDIE WELL PROSPECT
    - 49060 pyritic quartz-biotite-plagioclase schist (D Zone, drill core, DDH 30, 109.2 m)
    - 49064 quartz-pyrrhotite-pyrite microbreccia (D Zone, drill core, DDH 30, 77.85 m)
13. COPPER HILLS MINE
    - 49115 quartz porphyry with disseminated pyrite (underground drill core, CH 13, 166 ft.)
    - 49116 quartz porphyry with pyrite aggregate (underground drill core, CH 13, 185.5 ft.)

14. WONGAN HILLS PROSPECT

49163 quartz-arsenopyrite-pyrite-chalcopyrite vein in quartz-garnet-mica schist (drill core, DDH 1, 156.3 m)

15. BIG STUBBY PROSPECT

49118 massive sphalerite-chalcopyrite-pyrite (drill core, MBC 21B, 218.5 ft.)

16. NARLARLA MINE

49124 massive pyrite with colloform to arborescent sphalerite-galena aggregates (dumps adjacent No. 2 ore body)

17. ILGARARI MINE

49152 quartz-chlorite siltstone with replacive pyritic layer (drill core, IS75)

18. BEASLEY RIVER PROSPECT (Hardey Sandstone)

49168 contact metamorphosed (?) carbonaceous siltstone with pyritic aggregates (drill core, BRD 2, 388.5 ft.)

19. MOUNT GOLDSWORTHY MINE (Archaean)

20571 black shale with pyritic layers (120 ft level, main pit)

20. MULGINE HILL prospect

28695A coarse vein quartz and pyrite from vein in granitoid

21. LENNON FIND PROSPECT

44957 porphyroblastic quartz-garnet-chlorite-biotite schist with disseminated sphalerite, pyrite, chalcopyrite and galena (drill core, DDH Y 601, 180 ft.)

44958 massive pyrite-sphalerite-galena in quartzite (drill core, DDH Y 701, 171 ft.)

22. MOUNT PALGRAVE PROSPECT (Jillawarra) Formation)

42683 cleaved black silty pyritic shale with concordant pyrite lenses

42686 black silty pyritic shale with discordant sphalerite-pyrite veinlet (drill core, DDH 13, 74.7 m)

42689 black silty pyritic shale with small pyrite nodule and discordant sphalerite veinlet (drill core, DDH 13, 83.2 m)

23. MOUNT VERNON PROSPECT (Glen Ross Shale)

42467 black silty pyritic shale (drill core, DDH 2, 86.8 m)

24. JILLAWARRA PROSPECT

A.48507 silty pyritic shale of Devils Creek Formation (drill core JLWA 16, 101.6 m)

B.48566 massive pyrite-galena-sphalerite 30 m from fault zone in Discovery Chert (drill core, JLWA 14, 208.35 m)

APPENDIX 2

LIST OF GOLD MINES CONTAINING MINOR AMOUNTS OF COPPER MINERALS

1:250 000 sheet	Mining centre	Gold mines containing minor copper	Copper minerals associated
Balfour Downs	Mount Fraser	Mount Fraser (Starlight)	chalcopyrite
Belele	Garden Gully	Kyarra	azurite, chalcopyrite
	Meekatharra	Commodore	malachite
Boorabbin	Burbanks	Grosmont Group	azurite, chalcopyrite, malachite
Cue	Burnakura	Federal City	covellite
	Coodardy	Big Bell	chalcanthite, chalcopyrite
	Cuddingwarra	Victory United	chalcopyrite
	Cue	Great Fingall	chalcopyrite
		Hidden Treasure	chalcopyrite, chrysocolla
		Rubicon	chalcopyrite, chrysocolla
		Rubicon North	azurite, chrysocolla, malachite
		Comet	
		Day Dawn (San Diego mines)	
		Eclipse	
		Eclipse North	
Dixon Range	Panton River	Lady Kimberley	chalcopyrite
		Scottish Chief	chalcopyrite
		Star of Kimberley	azurite, chalcopyrite
Duketon	Erlistoun	Mistake	chalcopyrite
		Swincers Find	
Edjudina	Linden	Bindah	native copper
		Deep Well	
		Patricia South	chalcopyrite
		Pennyweight Pt	
		Yarri South	chalcopyrite, covellite
Glengarry	Gabanintha	Grants	azurite
		Lady Alma	chalcopyrite
		Leviathan	chalcopyrite
		Mountain View	azurite, chalcopyrite
		Tumblegum	azurite, chalcopyrite, chrysocolla
Jackson	Bullfinch	Bullfinch Prop.	azurite, bornite, malachite
	Koolyanobbing	Chadwick's Reward	azurite, malachite
	Mount Jackson	Marda	
	Golden Valley	Radio	
		Golden Valley	
Kalgoorlie	Coolgardie	*Bayleys*	*chalcopyrite*
		Black Prince	azurite, chalcopyrite, cuprite, malachite
		Lombard	azurite, chalcopyrite, cuprite, malachite
		Sydenham	azurite, chalcopyrite, cuprite, malachite
	Daveyhurst	Golden Pole	chalcopyrite
		Waihi	chalcopyrite
	Feysville	Michael Angelo	chalcopyrite
	Jourdie Hills	Derry's Own	chalcopyrite
		Associated	chalcopyrite, tennantite
	Kalgoorlie	Associated Northern Gold Mines	chalcopyrite, rickandite, tennantite
		Croesus Proprietary	chalcopyrite, chrysocolla
		Great Boulder	chalcopyrite, tennantite
		Ivanhoe	bournonite, chalcopyrite, covellite, tennantite
		Hidden Secret	bornite, chalcopyrite, tennantite, rickandite
		Kalgurli	bornite, rickandite
		Kapunda Boulder	malachite
		Lake View Consols	chalcopyrite
		Lake View South Extended	chalcopyrite
		Maritana	malachite
		North Kalgurli	chalcopyrite
		Oroya North	chalcopyrite
		Palmerston North	azurite, chalcocite, malachite
		Perseverence	chalcocite, chalcopyrite, olivenite, tennantite
		South Kalgurli	bornite, tennantite
	Kunanalling	Star of Fremantle	chalcopyrite
	Ora Banda	Good Hope	tennantite
		Last Hope	tetrahedrite
	Siberia	Merriwee King	chalcopyrite
		Victory	chalcopyrite
Kirkalocka	Paynesville	Windsor	azurite, malachite
Kurnalpi	Feysville	Feysville	
	Kanowna	Gentle Polly	chalcopyrite
		Golden Valley	
		White Feather Main Reef	chalcopyrite
	Mulgabbie	Mulgabbie	
		Perseverence	chalcopyrite
Laverton	Erlistoun	King of Creation	
	Laverton	*Just in Time*	
		Lancefield	chalcopyrite
		Red Flag	
		Rowena	
Leonora	Diorite King	Bower	
		Mount Stirling	chalcopyrite
	Lawlers	Mountain Queen	azurite, chalcocite, chrysocolla, malachite
	Leonora	Leonora Gold Blocks	azurite
Marble Bar	Marble Bar	Augusta	chalcopyrite
		Bohemia	chalcopyrite
		Coongan Star	malachite
		Corboys (Edelweiss)	
		Franklin	chalcopyrite
		Homeward Bound	chalcopyrite
		New Chum Railway	malachite
		True Blue	malachite

1:250 000 sheet	Mining centre	Gold mines containing minor copper	Copper minerals associated
	North Pole	Democrat	
		Leviathan	
	North Shaw	Auraria	Chalcopyrite, malachite
		Big Bertha	
		Dalton	
		Eldorado	chalcopyrite, malachite
		Nil Desperandum	azurite, cuprite
		Struck Oil	
	Tambourah	Tambourah United	
	Warrawoona	Bow Bells No. 1	chalcopyrite
		Blue Bar	
		Copenhagen	
		Fieldings Gully	
		Klondyke Boulder East	
		Lone Hand	chalcopyrite
		Prinsep	cuprite, malachite
	West Shaw	Trafalgar	chalcopyrite
Menzies	Comet Vale	Lake View	azurite, chalcopyrite, malachite
		Long Tunnel Extended	chalcopyrite
	Mount Ida	David Copperfield	chalcopyrite
		Federation	chalcopyrite
		Forest Belle	chalcopyrite
		Main Lode	chalcopyrite
		Meteor	chalcopyrite, malachite
		Octagon	native copper
		Timoni	chalcopyrite
	Mulline	Daydream	azurite, malachite
		Lady Gladys	chalcopyrite
Mount Ramsay	Mount Dockrell	Hard Labour	chalcopyrite
Ninghan	Fields Find	Fields Find	
		Langs Find	
	Goodingnow	Lake View	chalcopyrite
	Nyounda	Gnows Nest	chalcopyrite
Nullagine	Middle Creek	Barton	malachite
		Blue Spec	chalcopyrite
	Yandicoogina	Black and White	chalcopyrite
		Eastern	azurite, malachite
Peak Hill	Cashman's	Hard to Find	chrysocolla, malachite
	Mikhaburra	Waterloo	bornite, chalcopyrite, covellite, malachite
Perenjori	Rothsay	Rothsay (Woodley's Reward)	azurite, bornite, chalcocite, chalcopyrite, native copper, tenorite
	Warriedar	Aurum	chrysocolla
		Ironclad	azurite, chalcocite, chrysocolla, malachite
		Porcupine	chrysocolla
Port Hedland	Talga	Star of the North	chalcopyrite, malachite
Pyramid	Hong Kong	Empress	chalcocite
		Hong Kong (Queen Victoria)	chalcopyrite
		John Bull	chalcopyrite
	Station Peak	Pilgrims Rest	chalcopyrite
Ravensthorpe	Carragarup	Dr Jim	azurite, chalcocite, chalcopyrite
	Kundip	Alice Mary	malachite, olivenite
	Ravensthorpe	All for the Best	chalcopyrite
		Ballarat (Emily Hale)	
		Big Surprise	
		Birthday	
		Bulldog	olivenite
		Floater	chalcopyrite
		Grafter	cuprite
		James Henry	chalcopyrite
		Jim Dunn's Warder (Princess Royal)	chalcopyrite
		Jubilee	chalcopyrite
		Lucy	chalcopyrite
		Maori Queen	chalcopyrite
Roebourne		Asteroid	
		Azurite	
		Good Luck	
		Kensington	
		White Australia	
Sandstone	Barrambie	Sugarstone	chalcopyrite, covellite
	Birrigrin	Hawthorn (Birrigrin Gold Mines)	malachite
	Quinns	Phoenix Extended (Eastern Gift)	chalcopyrite, chrysocolla, tennantite
		Two Jacks	chalcopyrite, chrysocolla
	Sandstone	Sandstone	chalcopyrite
Sir Samuel	Bronzewing	Bronzewing Reward	chalcopyrite, covellite, malachite
		Malbie	chalcopyrite, covellite, malachite
	Darlot	Amazon	chalcopyrite
		Mermaid	chalcopyrite
		Monte Christo	chalcopyrite
	Kathleen Valley	Sulphide King	azurite, chrysocolla
	Sir Samuel	Bellevue Proprietary	azurite, chalcopyrite, chrysocolla, native copper
		Isidore	chrysocolla
		Sir Samuel	
		Sir Samuel North	
Southern Cross	Corinthian	Corinthian	chalcopyrite
	Marvel Loch	Jacoletti	chalcopyrite, pisanite
	Palmers Find	Yellowdine Development	chalcopyrite, tennantite
	Parkers Range	Macintosh	chalcopyrite
	Southern Cross	Central (Frasers)	chalcopyrite
		Greenmount	chalcanthite
		Revelation	azurite, chalcopyrite, malachite

APPENDIX 2—continued

1:250 000 sheet	Mining centre	Gold mines containing minor copper	Copper minerals associated
		Transvaal	chalcanthite
	Westonia	Edna May Deeps	chrysocolla
Widgiemooltha	Mount Monger	Minerva	chalcopyrite, covellite
		McMahon's Great Hope	chalcopyrite, malachite
	Paris Peninsula	Paris Mine	chalcopyrite
Wiluna	Wiluna	Weeloona	bournonite, malachite
		Wiluna Gold Corporation	tetrahedrite
Wyloo		Belvedere	
		Paulsen	
Yalgoo	Carlaminda	Ivanhoe	chalcopyrite
		Sovereign Prospecting	azurite, chalcopyrite, malachite, native copper
	Melville	Hard to Find	malachite
	Wadgingarra	Wadgingarra Main Reef	chrysocolla
		Whelock	

APPENDIX 3

LEAD MINES IN THE NORTHAMPTON BLOCK CONTAINING MINOR AMOUNTS OF COPPER MINERALS

Ajana 1:250 000 sheet

- Deebles
- Galena
- Gallaghers Pyromorphite Lode
- Geraldine Lead Mine
- Geraldine South
- Mary Springs
- Surprise
- Surprise South
- Three Sisters North
- Two Boys
- Wheal Ina
- MC 15

Geraldton 1:250 000 sheet

- Baddera
- Cow Rock
- Gurkha
- Mendip
- Nooka
- Paringa
- Protheroe
- Shepherds
- Wheal Ellen
- Wheal Fortune Extended

APPENDIX 4

LIST OF COPPER MINES, PROSPECTS AND OCCURRENCES ARRANGED BY 1:250 000 SHEET AREAS

Name	Major Metals	Page
AJANA		
Geraldine	Cu Pb Ag	148
Gibsons	Cu	148
Hennings	Cu	149
Ouraka	Cu	150
Tambarra	Cu	150
ASHTON		
Bindoola Creek	Cu	31
Durack River	Cu	32
New York	Cu	32
BALFOUR DOWNS		
Blowhole (Mount McLarty)	Cu	90
Coorapline Well	Cu	90
Googhenama Creek	Cu	90
Turramunda Rock Hole	Cu	90
BARLEE		
Diemals	Cu	128
BELELE		
Abbotts	Cu	139
Chunderloo	Cu Au	128
BENTLEY		
Scamp Hill	Cu	117
BREMER BAY		
Naendip	Cu	157
CAMBRIDGE GULF		
Maggys Creek	Cu	33
Mendena Creek	Cu	33
Menuairs Dome Northeast	Cu	31
Mount Edith East	Cu	32
Mount Edith North	Cu	32
Mount Fraser West	Cu	33
Pentecost Range	Cu	32
Pentecost River	Cu	32
Petes Find	Cu	51
Redbank	Cu	51
Shangri-La	Ag Pb Cu	37
Spring Creek	Cu	32
Terrace Hill North	Cu	33
The Paps	Cu	33
CAMDEN SOUND		
Wilson Point	Cu	37
CHARNLEY		
Mount Hart	Cu	37
COLLIER		
Brumby Creek	Zn Cu Pb	106
Butcher Bird	Cu	105
Ilgarari Main	Cu	102
Ilgarari Northeast	Cu	102
Koode Magi	Cu	106
Kumarina	Cu	104
Kumarina North	Cu	104
Kumarina Northeast	Cu	105

Name	Major Metals	Page
Collier Contd		
Kumarina Open Cut	Cu	104
Morawa Well	Cu	106
Neds Gap	Cu	106
Rinaldi	Cu	105
Scotty	Cu	106
Towers Find	Cu	106
Wonyulgunna	Cu	113
COOPER		
Skirmish Hill	Cu	117
Tollu	Cu	117
CORRIGIN		
Boyagarra	W Cu	145
CUE		
Callie Soak	W Mo Cu	145
Cuddingwarra North	Cu	144
Eelya North	Cu Zn	125
Molybdenite	Mo Co Cu	145
Mount Eelya	Cu	144
Mount Mulcahy	Cu	127
Recovery	Mo W Cu	145
DAMPIER		
Canhams	Cu	81
Devil Creek	Cu	78
Mount Sholl	Cu Ni	82
Ruth Well	Ni Cu	82
Tom Well	Cu	81
Twin Table	Cu	81
DIXON RANGE		
Bungle Bungle Outcamp	Cu	52
Corkwood	Ni Cu	49
Corkwood West	Cu	48
Fishole Waterhole	Cu	37
Forrest Creek	Cu	53
Frank River	Cu	47
Froghollow Spring	Cu	48
Keller Creek	Ni Cu	49
Mabel Downs East	Cu	48
McHales	Cu	48
Mount Coghlan Northwest	Cu	47
Mount Elder	Cu	51
Osmond Creek	Cu	47
Osmond Range	Cu	40
Osmond Range West	Cu	37
Roses Bore	Cu	48
Sally Malay	Ni Cu	49
Tickalara Bore	Cu	48
DUKETON		
Cosmo Newberry	Cu	141
EDMUND		
Anticline (Bali High)	Cu Pb Zn U Au Ag	94
Bali High East	Cu Pb Zn Bi As Ag U	94
Casleys	Cu Pb Bi	93
High Range	Zn Cu Pb	106
Joy Helen	Cu Pb	107

Name	Major Metals	Page
Edmund Contd		
Kooline	Pb Cu	94
Latham	Pb Cu	107
Ledge	Cu	94
Mangaroon	Pb Cu Au Ag	99
Mount Isabella	Pb Cu	107
Mount Palgrave	Zn Cu Pb	106
Mundong Well	U Pb Cu	99
Stockyard Creek	Cu Sb As	94
Walker	Cu	99
GERALDTON		
Gelirah	Pb Cu Zn	147
Gwalla	Cu	149
Martins Spring	Cu Pb Ag	149
Narra Tarra	Cu Ag Au	149
Narra Tarra East	Cu Pb	149
Unaring	Cu	150
Victoria	Cu	150
Wanerenooka	Cu	150
Wheal Alpha	Cu	150
Wheal Beta	Cu	150
Wheal Fortune	Cu	150
Wheal Margaret	Cu	151
White Peak	Cu	151
Yanganooka	Cu	151
Yankee Crossing	Cu	151
GLENBURGH		
Dalgety Downs	Cu	98
Unnamed Occurrences	Cu	98
GLENGARRY		
Lady Alma	Cu	139
Mountain View	Au Cu	139
Tumblegum	Cu Au	139
GORDON DOWNS		
Bulman Waterhole	Cu	46
Coolibah Creek	Cu	
Golf Course	Cu Zn Pb	44
Ilmars	Zn Cu Pb	45
Koongie Park	Cu	45
Little Mount Isa	Zn Cu Pb	45
Mount Kinahan	Cu	47
GUNANYA		
Boondawari Creek	Cu	107
JACKSON		
Carterton	Au Cu	142
Marda	Cu	142
KALGOORLIE		
Argus Show	W Cu Pb	145
Goongarrie	Au Cu	142
Lady Bountiful	Au Cu	144
Mount Pleasant (New)	Cu	144
Mount Pleasant (Old)	Cu Au	144
KIRKALOCKA		
Narndee	Cu Zn	129
KURNALPI		
Beeck	Cu	143
Carr Boyd Rocks	Ni Cu	145
Corsair	Au Cu	143
Emu Dam	Cu	143
Hopeless Dam	Cu	142

Name	Major Metals	Page
LANSDOWNE		
Coolan Creek Yard	Pb Cu	37
Goads Yard East	Cu Pb	48
Little Fitzroy River	Cu	32
Narrie Range	Cu	36
Number 1 prospect	Cu	36
Number 14 show	Cu	36
Teronis Yard	Cu	32
Tumagee Yard	Cu Pb	48
LAVERTON		
Anaconda	Cu Zn	122
Camel Humps	Cu	144
Crayfish Creek	Zn Cu	124
Mitika Well	Cu	144
Mount Margaret	Cu	141
Mount Morven	Au Cu	141
Nangaroo	Cu Zn	122
Pearl Shell Well	Cu	125
Rio Tinto	Cu Zn	122
Rowena	Au Cu	141
Trafalgar	Cu	122
Welcome Well West	Cu	125
LENNARD RIVER		
Colemans Creek	Cu Zn Pb	45
Narlarla	Pb Zn Cu	159
Ord Gap	Cu	48
Top Springs	Cu Pb Zn	45
Turtle Creek	Zn Pb Cu	45
LEONORA		
Agnew-Lawlers Group	Cu	141
Bower	Au	141
Bungarra	Cu	141
Lawlers West	Cu	141
Mertondale	Mo Cu Pb Zn	145
Teutonic Bore	Cu Zn	125
Wildara	Cu	141
LISSADELL		
Behn Gorge	Cu	53
BHP	Cu	35
Bow River	Cu Ni	49
Calamondah	Cu	37
Camel Creek Yard	Cu	48
Campbellmerry	Cu	33
Chamberlain Valley	Cu	31
Dunham Crossing	Cu	53
Dunham River	Cu	53
Dunham River Jump Up	Cu	48
Durack Range	Cu	35
Durack Range South	Cu	36
Excelsior Range	Cu	48
Grimwood Creek	Cu	33
Lincoln Yard	Cu	52
Martins flourite	F Pb Cu	37
Martins silver-lead	Ag Pb Cu	37
Moonlight Valley Yard	Cu	37
O'Donnell Range	Cu	48
Plants	Cu	34
Ragged Range	Cu	51
Rosewood Wall	Cu	52
Wild Dog Soak	Cu	53

Name	Major Metals	Page
LONDONDERRY		
Cape Bougainville	Cu	36
Drysdale River Estuary	Cu	36
MARBLE BAR		
Abydos Northeast	Cu	77
Bassetts	Cu	82
Big Stubby	Zn Pb Cu Ba	66
Boobina Creek	Cu	79
Breens	Cu	73
Coffin Bore	Cu	77
Copenhagen West	Cu	79
Copper Hills	Cu	75
Copper Hills South	Cu	76
Copper Hills West	Cu	76
Emu Creek East	Cu	79
Glen Herring	Cu	90
Hazelbys	Cu	68
Kellys	Cu	76
Marble Bar South	Cu Au	77
Mount Francisco	Cu	82
Mount Webber SE	Ta Cu	80
North Shaw	Cu Au	79
Ryans	Cu	77
Salgash	Cu	77
Shark Gully	Cu	79
Stannum Northeast	Cu	77
Stannum West	Cu	77
Wilson	Cu	79
Woodstock	Cu Au	79
MEDUSA BANKS		
Helby River	Cu	32
Helby River West	Cu	32
Lyne River	Cu	31
Lyne River North	Cu	31
Mount McMillan South	Cu	33
MENZIES		
Donna Gnamma Hole	Cu	141
Forrest Belle	Au Cu	141
Little Wonder	Au Cu	141
Mount Ida Centre	Au Cu	141
Mulline	Au Cu	141
MINIGWAL		
Irwin Hills	Cu	144
MOORA		
Wongan Hills (District)	Cu	143
Wongan Hills (prospect)	Cu Ag	130
MOUNT BRUCE		
Beasley River	Cu	89
Brockman	Cu	89
Edneys	Cu	89
Minthicoondunna	Cu	89
MOUNT EGERTON		
Glen Ross	Zn Cu	106
Jilliwarra	Zn Pb Cu	113
Mulgul	Cu	106
MOUNT ELIZABETH		
Barnett River Gorge	Cu	36
Chamberlain Valley	Cu	31
Karunjie	Cu	37
Number 3 show	Cu	35
Police Creek	Cu	34
Traine River	Cu	34

Name	Major Metals	Page
MOUNT PHILIPS		
Arthur River	Cu	98
Kingfisher	Cu	99
McCarthy Find	Pb Cu	107
Mooloo Downs	Cu	98
Ti-Tree Well	Cu	99
Yinnietharra	Cu	98
MOUNT RAMSAY		
Black and Glidden	Pb Cu	48
Bullock Bore	Cu	48
Dead Horse Creek	Pb Cu	48
Eastmans Bore	Cu Pb Zn	44
Emull	Zn Pb Cu	46
Hangmans Creek Bore	Cu	45
Koongie Park Southwest	Cu Zn Pb	44
Margaret River	Cu	48
McLintock Range	Cu	48
Me No Savvy	Cu	48
Mount Amherst East	Cu	46
Mount Angelo	Cu	44
Mount Angelo South	Cu	49
Mueller Range	Cu	36
Taylor River	Cu	48
MURGOO		
Twin Peaks	Cu	143
NEWDEGATE		
Colemans	Mo Cu	145
Copper King	Cu Zn	139
Last Venture	Cu Zn	139
McCulloch	Cu	157
Netty	Cu	143
NEWMAN		
The Bend	Cu	89
Bull	Cu	88
Central	Cu	89
Ironstone	Cu	89
Mount Robinson	Cu	89
Wonmunna	Cu	89
NINGHAN		
Fields Find	Au Cu	142
Langs Find	Au Cu	142
Mount Gibson—Paynes Crusoe	Au Cu	142
Warriedar	Cu	141
NORSEMAN		
Gnama South	Ni Cu	157
Rungine	Cu	128
Talbot	Ni Cu	157
NULLAGINE		
Bridget	Cu	67
Cookes Creek	W Cu	81
Coondamar Creek	Cu Pb Zn	67
Copper Gorge	Cu Zn	66
Gobbos	Cu Mo	73
Lennon Find	Zn Pb Cu	67
Lightning Ridge	Cu Mo	73
Lionel	Cu	78
McPhee Creek East	Cu Mo	72
Middle Creek	Au Cu	77
Otways	Cu	67

Name	Major Metals	Page
PATERSON RANGE		
Various unnamed	Cu Cu-Au	85
Telfer	Au Cu	85
PEAK HILL		
Cashman	Cu	113
Green Dragon	Cu	112
Horseshoe Lights	Cu Au	112
Motter B	Cu	113
Ricci	Cu	111
Rooney	Cu	111
Thaduna	Cu	110
Thaduna North	Cu	111
PERENJORI		
Arrino	Cu	154
Baxter	Cu	154
Harrison	Cu	142
Mount Misery	Cu	155
Mount Muggawa	Cu	155
Mount Scratch	Cu	154
PINJARRA		
Armadale	Zn Pb Cu	145
Mundijong	Zn Pb Cu	145
Serpentine	Zn Pb Cu	145
PORT HEDLAND		
Boodarrie	Cu	81
PRINCE REGENT		
Augustus Island	Cu	36
Brecknock Harbour	Cu	36
Glenelg River	Cu	37
Saint George Basin	Cu	36
PYRAMID		
Black Gin Point	W Cu	80
Egina	Cu	69
Evelyn	Cu Zn	69
Kopje	Cu	78
Quamby	Cu	78
Pilbara	Cu	78
RAVENSTHORPE		
Alice Mary	Au Cu	133
Ard Patrick	Cu	133
Australia	Cu	133
Ballarat	Cu Au	137
Big Surprise	Cu	136
Birthday	Cu Au	133
British Flag	Cu Au	133
Christmas Gift	Au Cu	133
Commonwealth	Au Cu	137
Comstock	Cu	133
Copper Horseshoe	Cu	133
Desmond	Cu Au Ag	133
Desmond Central	Cu	133
Elverdton	Cu Au Ag	135
Elverdton South	Cu	133
Elverdton Welcome Stranger	Cu	133
Flag	Au Cu Ag	136
Floater	Au Cu	133
Gem	Au Cu	137
Gem Consolidated	Au Cu	137
Grafter	Au Cu	133
Great Oversight	Cu	133
Ravensthorpe Contd		
Grimsby	Cu Au Ag	133
Harbour View	Au Cu Ag	136
Hillsborough-Fairplay	Au Cu	136
Ironclad	Cu Au Ag	133
Kuracca	Cu Au Ag	133
Last Chance	Cu Au Ag	137
Last Chance North Extended	Cu	133
Last Chance Proprietary	Cu Au	133
Little Wonder	Cu Au	133
Lone Star	Cu Au	133
Marion Martin	Au Cu	138
May Day	Au Cu	133
Mount Benson	Au Cu	137
Mount Benson East	Au Cu	137
Mount Cattlin	Au Cu	137
Mount Desmond	Au Cu	135
Surprise	Au Cu	138
ROBERTSON		
Jimblebar	Cu Zn	68
ROEBOURNE		
Carlow-Castle	Cu Au Ag	80
Ena	Cu	80
Federal City	Cu	62
Fortune	Cu Au	81
Good Luck	Cu Au	81
Lilly Blanche	Cu	80
Mons Cupri	Cu Zn Pb	62
Mons Cupri NW	Cu Zn	66
Rushall	Cu	62
Sherlock Bay	Ni Cu	82
Stranger	Cu	62
Western Hill	Cu	66
Whim Creek	Cu Zn Pb	56
RUDALL		
Camel Rocks	Cu	84
Mount Cotten	Cu	84
Mount Cotten North East	Cu	84
South Rudall dome	Cu Zn	84
Yandagooge	Cu Pb Zn	84
SANDSTONE		
Barrambie	Cu	144
Quinns	Cu Zn	130
SIR SAMUEL		
Kathleen-Cobar Copper King	Cu	140
Kathleen Valley	Cu	140
Mount Mann	Cu	140
Mount Sir Samuel	Au Cu	140
Shepherd-Copper King	Cu	140
TALBOT		
Mount Eliza	Zn Pb Cu	117
Mount Elvire	Cu Zn	117
Mount Palgrave	Zn Pb Cu	117
Pussy Cat Hill	Cu	117
TUREE CREEK		
Goobaroo Pool	Cu	93
Mount Blair South	Cu	93
Soldiers Creek North East	Cu Au	93
Station Creek	Cu Pb	93
Windy Ridge	Cu	92
WILUNA		
Wiluna (gold mine)	Au Cu	187

Name	Major Metals	Page
WIDGIEMOOLTHA		
Higginsville	Cu	143
Lake Dundas	Cu	143
Mount Thirsty Sill	Cu	143
Paris	Au Cu	143
Yardilla South	Cu	157
WYLOO		
Belvedere	Cu Ag Pb	90
Big Blow	Cu	92
Blacks	Cu	90
Cane Hill	Cu	92
Coppermine Bore	Cu	99
Lockes	Cu	92
Meilga	Cu Au	98
Mindel Well	Cu	90
Minga Bore	Cu	98
Nanutarra	Ag Pb Cu	99
Paulsen	Cu Au	90
Range Well East	Cu	98
Rundles Hill	Cu	91
Warrada Creek Well	Cu	107
YALGOO		
Buddadoo Range South	Cu	141
Bunnawarra	Cu	129
Golden Grove	Cu Zn	126
Wadgingarra (Olive Queen)	Au Cu	141
YAMPI		
Amphibolite	Cu	37
Chianti	Zn Cu Pb	45
Coppermine Creek	Cu	37
Grants Find	Cu	47
High Range West	Cu	36
Limestone Spring	Ni Cu	49
Mangrove Creek	Cu	47
McLarty Range	Cu	34
Monarch	Cu	47
Mondooma	Cu	47
Mount Nellie Southeast	Cu	47
Mundurrul River	Cu	33
Rough Triangle	Cu	47
Yampi Contd		
Secure Bay	Cu	48
Tarraji	Cu	47
Townshend River	Cu	47
Wilsons Reward	Cu	47
YANREY		
Bullajacka Well	Cu	96
Claypan Well	Cu	99
Emu	Ag Pb Cu	99
Euro	Cu	96
Hornet Well	Cu	96
Proctor Gully	Cu	96
Range	Ag Pb Cu	99
Turtle	Cu Pb	97
Uaroo Group	Cu Pb Ag Au	96
Victoria	Cu	96
Weston Group	Cu	96
P.A. 322	Cu	96
YARRALOOLA		
Beechworth	Cu	91
Kangaroo	Cu	91
Niven	Cu	91
Red Hill	Cu	91
Red Hill South	Cu	91
Yannery Hill	Cu Zn	70
Yarraloola	Cu Pb Zn	97
YARRIE		
Baramine	Cu Ag	90
Baramine South	Cu Ag Pb	89
Callawa	Cu	78
Camel Hump South	Cu	90
Yarrie South	Cu Zn Ag	78
YOUANMI		
Freddie Well	Zn Cu	129
Fitz Bore	Cu	141
Mount Alfred	Cu	128
Youangarra	Cu Ni	144
Yuinmery	Cu	129

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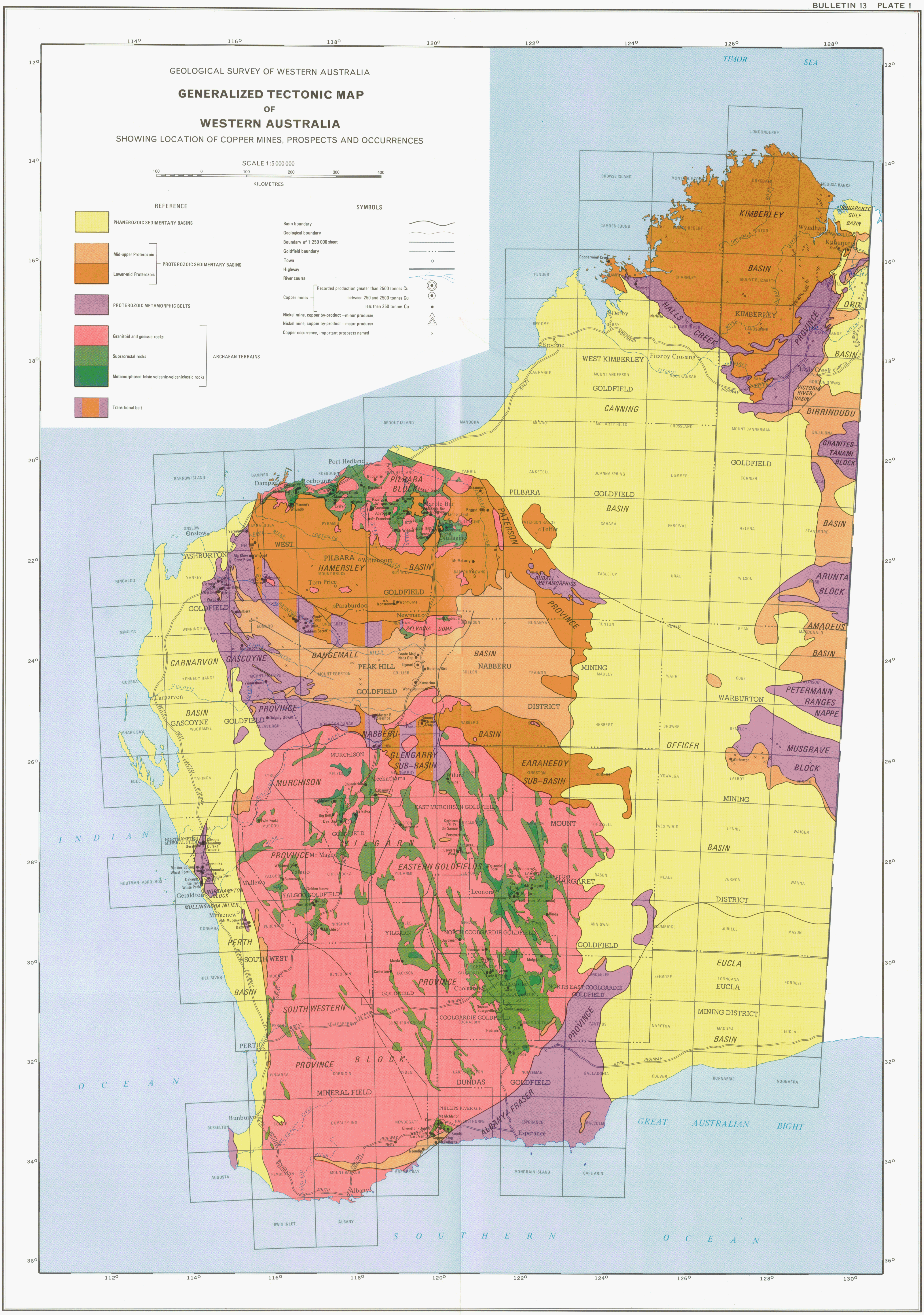
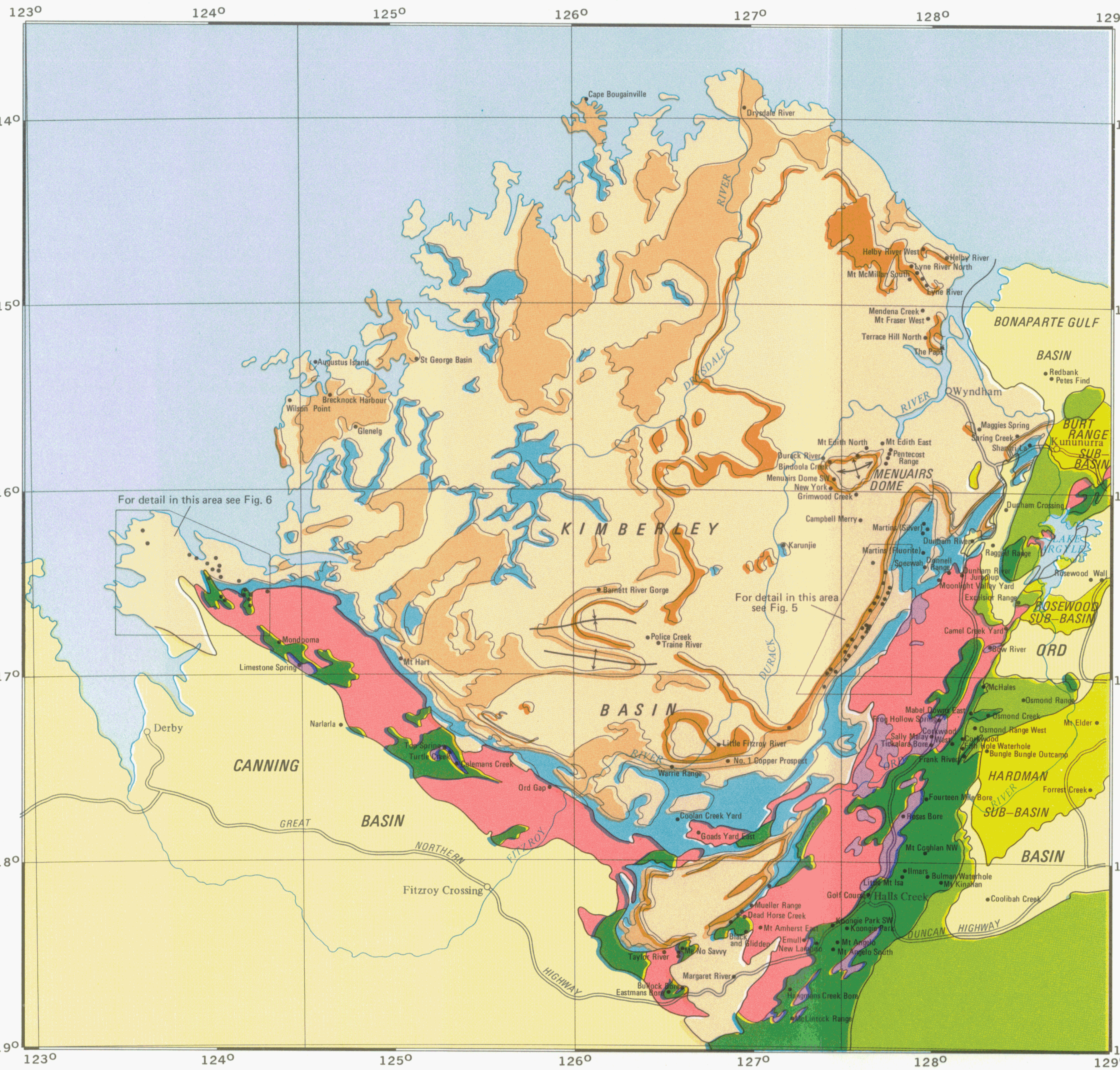

GEOLOGICAL SURVEY OF WESTERN AUSTRALIA
GENERALIZED TECTONIC MAP
OF
WESTERN AUSTRALIA
SHOWING LOCATION OF COPPER MINES, PROSPECTS AND OCCURRENCES
SCALE 1:5 000 000
100 0 100 200 300 400
KILOMETRES
REFERENCE
PHANEROZOIC SEDIMENTARY BASINS
Mid-upper Proterozoic
Lower-mid Proterozoic
PROTEROZOIC SEDIMENTARY BASINS
PROTEROZOIC METAMORPHIC BELTS
Granitoid and gneissic rocks
Supracrustal rocks
Metamorphosed felsic volcanic-volcaniclastic rocks
ARCHAEAN TERRAINS
Transitional belt
SYMBOLS
Basin boundary
Geological boundary
Boundary of 1:250 000 sheet
Goldfield boundary
Town
Highway
River course
Copper mines
Recorded production greater than 2500 tonnes Cu
between 250 and 2500 tonnes Cu
less than 250 tonnes Cu
Nickel mine, copper by-product – minor producer
Nickel mine, copper by-product – major producer
Copper occurrence, important prospects named
TIMOR SEA
INDIAN OCEAN
SOUTHERN OCEAN
GREAT AUSTRALIAN BIGHT
KIMBERLEY BASIN
HALLS CREEK PROVINCE
KIMBERLEY
WEST KIMBERLEY GOLDFIELD
CANNING BASIN
BIRRINDUDU
GRANITES–TANAMI BLOCK
ARUNTA BLOCK
AMADEUS BASIN
PETERMANN RANGES NAPPE
MUSGRAVE BLOCK
OFFICER BASIN
WARBURTON MINING DISTRICT
PILBARA BLOCK
PILBARA GOLDFIELD
HAMERSLEY BASIN
PATERSON PROVINCE
RUDALL METAMORPHICS
BANGEMALL BASIN
PEAK HILL GOLDFIELD
NABBERU BASIN
EARAHEEDY SUB-BASIN
GLENGARRY SUB-BASIN
GASCOYNE PROVINCE
CARNARVON BASIN
ASHBURTON GOLDFIELD
GASCOYNE GOLDFIELD
MURCHISON GOLDFIELD
YILGARN BLOCK
EASTERN GOLDFIELDS PROVINCE
SOUTH WESTERN PROVINCE
MOUNT MARGARET GOLDFIELD
NORTH EAST COOLGARDIE GOLDFIELD
NORTHAMPTON BLOCK
PERTH BASIN
ALBANY–FRASER PROVINCE
EUCLA BASIN
DUNDAS GOLDFIELD
PHILLIPS RIVER G.F.
Port Hedland
Broome
Derby
Wyndham
Kununurra
Fitzroy Crossing
Halls Creek
Telfer
Onslow
Carnarvon
Newman
Tom Price
Paraburdoo
Wittenoom
Marble Bar
Nullagine
Meekatharra
Wiluna
Leonora
Laverton
Kalgoorlie
Coolgardie
Geraldton
Mullewa
Mingenew
Perth
Bunbury
Albany
Esperance
Ravensthorpe



REFERENCE

*PHANEROZOIC BASINS and SUB-BASINS

VICTORIA RIVER and BIRRINDUDU BASINS

KIMBERLEY BASIN

*Elgee Siltstone

*Carson Volcanics

*Hart Dolerite

HALLS CREEK PROVINCE

Granitoid rocks and younger supracrustal rocks (Whitewater Volcanics)

Variably metamorphosed mafic-ultramafic intrusive rocks

*Older supracrustal rocks (Halls Creek Group, Tickalara Metamorphics)

*Note: Contains cupriferous stratigraphic units

SYMBOLS

Basin boundary

Geological boundary

Syncline

Anticline

Anticline showing plunge

Copper occurrence

Highway

Town

River

GEOLOGICAL SURVEY OF WESTERN AUSTRALIA

GENERALIZED GEOLOGICAL MAP

OF THE

KIMBERLEY REGION

SHOWING TECTONIC PROVINCES, SELECTED CUPRIFEROUS STRATIGRAPHIC UNITS AND COPPER OCCURRENCES

SCALE

50 0 50 100 150

KILOMETRES