GEOLOGICAL SURVEY OF WESTERN AUSTRALIA

BULLETIN 127

GEOLOGY OF THE PILBARA BLOCK AND ITS ENVIRONS

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FRONTISPIECE

Enhanced Landsat image (ERTS 1) of an area 185 km x 185 km in the southeastern part of the Pilbara Block. Comparison with Plate 1 shows that pale areas of the image correspond to Archaean granitic batholiths whereas darker areas represent volcanics (predominantly mafic) of Archaean greenstone belts (more banded) and Lower Proterozoic formations. Clearly defined features include the Mosquito Creek Formation (striped, centre right) dolerite dykes (dark lines) trending north-northeast across the batholiths, and the valley of the Fortescue River (bottom). Landsat 1, Scene No. 1148-01282, Band No. 5, imagery by NASA, tapes supplied by the EROS program, USGS, scan line removal and contrast stretching by Division of Mineral Physics, CSIRO, Sydney.

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GEOLOGY OF THE PILBARA BLOCK AND ITS ENVIRONS

by

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FOREWORD

Since the first significant gold discoveries at Mallina and Pilbara Well in 1888, the Pilbara Block has played an important role in the development of Western Australia's mining industry. As revealed by extensive prospecting around the turn of the century, the area contains widespread and varied mineralization, and still offers much scope for mineral exploration.

It was largely because of this mineral potential that the Geological Survey of Western Australia carried out extensive regional surveys of parts of the Pilbara Block in the early 1900s and again in the 1950s. These surveys resulted in the publication of Bulletins 15, 20, 23, 40, 41, 104 and 115.

Beginning in the early 1960s, the Survey embarked upon a programme of systematic sheet mapping at a scale of 1:250 000 which involved, in part, the remapping of some earlier 4-mile sheets. This mapping programme took place at a time of growing awareness of the importance of studying the Earth's early history as represented in its ancient rocks. The Pilbara Block was recognized as an outstanding example of well-exposed Archaean and Proterozoic rocks representing some 1 000 million years of crustal evolution and containing the oldest rocks known in Australia.

Accordingly, when the mapping was completed in 1976, the Author was instructed to compile all available information, including the results of regional mappers, mineral explorers and various researchers, into a Bulletin covering the whole of the Pilbara Block and adjacent areas of Proterozoic rocks.

Notable achievements of the recent mapping included completely new stratigraphic and structural interpretations of the Pilbara Block, and this Bulletin provides the first comprehensive descriptions of these. It also describes all the Block's important mineral deposits, and discusses controls of mineralization.

The Bulletin will not only be of considerable assistance to those engaged in future mineral exploration and other types of geological investigation in the Pilbara Block, but will also be a valuable source of information for those studying other Archaean terrains of the world.

A. F. TRENDALL
DIRECTOR

September 1982

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CHAPTER 1

Introduction

THE AREA DESCRIBED

The Pilbara Block is an Archaean tectonic unit in the northwest of Western Australia. Approximately 60 000 km^2 in area, the block is bounded by the Indian Ocean to the northwest, unconformities against Lower Proterozoic rocks to the west, south and east, and by Phanerozoic rocks to the north and northeast. The area contains granitic, sedimentary and volcanic rocks, which isotope geochronology has established include some of the most ancient (about 3 500 million years old) on Earth.

The main purpose of this bulletin is to describe the area's Archaean geology, but younger rocks north of the Fortescue River in the west, and north of latitude 22° 15′S in the east are also discussed.

SETTLEMENT, COMMUNICATIONS AND INDUSTRY

Figures obtained by the 1976 Census reveal that the total population of the area is approximately 26 000, by far the greater proportion being concentrated in the principal towns, Port Hedland (11 144), Karratha (4 243), Dampier (2 727), Wickham (2 312), Roebourne (1 368), Goldsworthy (989), Shay Gap (856), Marble Bar (262) and Nullagine (less than 200). Numerous pastoral properties averaging about 200 000 ha are present, although some are no longer being operated.

A sealed highway connects Goldsworthy to Port Hedland, Roebourne, Karratha and Perth (1 946 km), and a gravel highway links Port Hedland with Marble Bar, Nullagine and Newman (thence sealed to Perth). Graded earth roads connect Port Hedland to Wittenoom, Goldsworthy to Shay Gap, and Roebourne to Wittenoom. Station roads of variable quality provide reasonable access to much of the area.

Company-owned railways, used for transporting iron ore, link Port Hedland with Newman, Goldsworthy and Shay Gap; Cape Lambert (Wickham and Roebourne) with Pannawonica; and Dampier with Tom Price and Paraburdoo. Frequent air flights operate from Perth to Port Hedland and Karratha, and local flights or road services provide connections to nearby towns.

Pastoral production in the area commenced shortly after F. T. Gregory's discovery of the Fortescue, De Grey and Oakover Rivers in 1861. His reports of good grazing lands soon led to the establishment of sheep stations by pastoralists from farther south. Sheep and cattle farming have become unprofitable in recent years, and work on many of the properties in the area has been suspended.

Copper was first found at Roebourne in 1872 (Simpson and Gibson, 1907) and 60 tonnes were exported from Cossack in 1873. The Pilbara Goldfield was proclaimed in 1888 following a discovery of gold at Mallina, and one month later a nugget weighing

3.95 kg (127 ozs) was picked up near Pilbara Well. A gold rush followed, and mines were rapidly established at Marble Bar, Nullagine, Tambourah, Bamboo Creek, Warrawoona, Talga Talga and many other centres. Intensive prospecting led to the discovery of copper, lead, asbestos, tin, tantalite, diamonds and iron ore, but few of the deposits proved large. The gold industry declined after 1955 and was replaced by mining of cupreous ore, cassiterite and manganese. Iron ore mining commenced at Goldsworthy in 1966, and at Shay Gap in 1972. Total production from these mines to the end of 1977 was about 67 million tonnes of ore (average grade, 64 per cent Fe).

Port Hedland is chiefly an outlet for iron ore mined at Newman, Goldsworthy and Shay Gap. Dampier fills a similar role for Tom Price and Paraburdoo, and Wickham serves Cape Lambert, the port handling iron ore from Pannawonica. Pelletizing plants operate at Dampier and Cape Lambert, and solar salt projects have been established at Dampier and Port Hedland.

Tourism is a growing industry for such centres as Dampier, Port Hedland, Roebourne (the old port of Cossack being a special attraction) and Marble Bar.

CLIMATE

The area is typical of arid steppes on the Western side of continents at corresponding latitudes. Throughout most of the year the area's weather is controlled by an anticyclonic belt to the south which produces dry, warm to hot winds from the east and southeast. During the summer months this pressure system is commonly disturbed by intense cyclones passing southwestwards parallel to and generally about 100 to 200 km off the Pilbara coast. In some cases these depressions veer inland giving sudden torrential rains accompanied by winds up to 200 km per hour in velocity. The heaviest rainfall ever recorded in one day in Western Australia, 747 mm, fell at Whim Creek during a cyclone in 1898. Average annual rainfall is approximately 300 mm, but annual evaporation is between 2 300 and 2 600 mm.

Rainfall and temperature data for Port Hedland, Roebourne and Marble Bar are summarized in Table 1.

TABLE 1. AVERAGE RAINFALL (mm) AND TEMPERATURE (°C) RECORDINGS AT PORT HEDLAND, ROEBOURNE AND MARBLE BAR

Town	*Hottest month*	*Coldest month*	*Wettest month*	*Driest month*
Port Hedland	March Max. 35.2 Min. 25.3	July Max. 26.3 Min. 13.1	March 85	September 1.0
Roebourne	December Max. 38.7 Min. 24.8	July Max. 26.1 Min. 13.0	March 65	October 0.8
Marble Bar	December Max. 41.9 Min. 25.6	July Max. 27.0 Min. 11.3	February 75	September 1.0

Data from Bartlett (1976)

VEGETATION

The low and erratic rainfall, combined with the high rate of evaporation, severely restricts the variety and density of vegetation in the area. Away from the watercourses only the hardiest of drought-resistant grasses and shrubs can survive. Most hills and scree slopes are covered by spinifex (*Triodia* spp.) with scattered stunted eucalypts such as the rough-leafed gum and snappy gum. Large trees, usually river gum, cajabut, coolibah and bloodwood are confined to river courses and the larger creeks. Shrubs and wattles grow on the drier and shallower soils of the plains. The dominant grass is spinifex, except close to the coast, where samphire flourishes. The intertidal zone is commonly occupied by dense growths of mangrove.

There is little relationship between geology and vegetation types, local hydrological factors having a dominating influence.

PHYSIOGRAPHY

As noted by Jutson (1950), the physiography of the area results from the incomplete dissection of an ancient peneplain, part of the "Great Plateau of Western Australia". North of the Fortescue River, Jutson (1950, p.64) named this old land surface the "Nullagine Plateau", but it is now commonly referred to as the "Hamersley Surface" (Campana and others, 1964).

In view of the area's size its relief is relatively subdued. As can be seen from Figure 1 the highest ground attains an elevation of only 618 m above sea level (a.s.l.). The most impressive topographic features of the region are scarps produced by progressive backward erosion of the Hamersley Surface. Some of these scarps (e.g. south of Shay Gap) are up to 100 mm in height.

From the shoreline of the Indian Ocean the general elevation of the present land surface increases southwards at an average rate of 2 m per kilometre. The highest part of the area lies close to its southern margin and all principal watercourses, except the De Grey River, are consequent rivers flowing northwards. The courses of these bear little relationship to the geology of the areas that they traverse and the drainage system is clearly superimposed.

Figure 1 illustrates the area's physiography using a subdivision which has evolved during the Geological Survey's mapping between 1956 and 1975.

PLATEAU

The Hamersley Surface is preserved (a) on Proterozoic rocks as yet undissected by the headwaters of the area's river system and (b) on rocks extremely resistant to erosion (especially banded iron-formation). The first type of plateau country is restricted to the southern and southeastern parts of the area. On the Chichester Range where the plateau is underlain by basaltic rock its surface is a poorly drained plain covered by large expanses of alluvial and eluvial clay (gilgai). Between the Oakover and Nullagine Rivers various types of rock underlie the plateau but a silicified chert breccia is most commonly responsible for its preservation. In such places the Hamersley Surface is represented by low rounded hills with fans of colluvium. Calcrete, 50 km southeast of

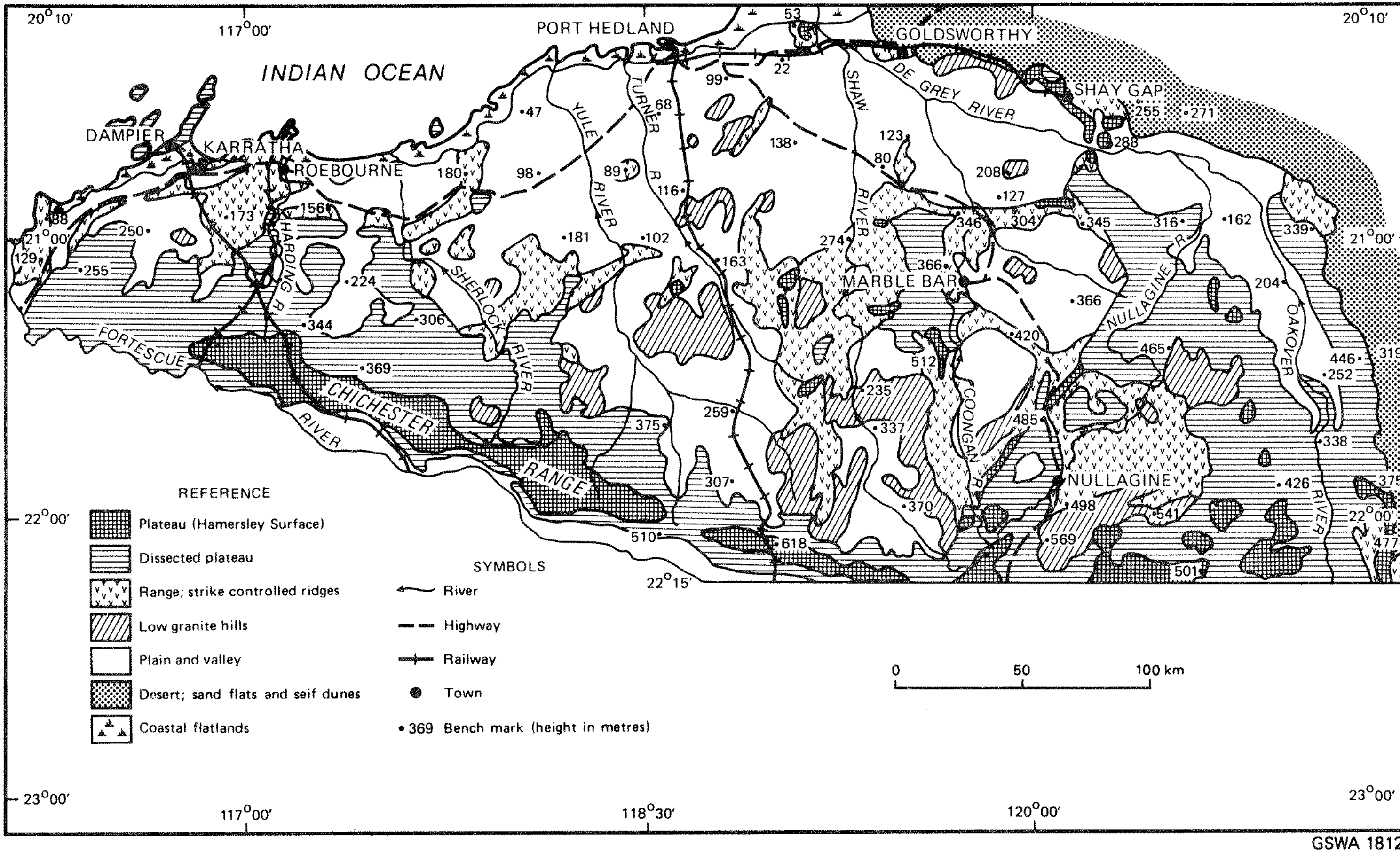

Figure 1. Physiographic divisions of the Pilbara Block.

Nullagine and in the valley of the Oakover River, is considered to represent a lacustrine deposit on the ancient peneplain, chiefly because of its common association with Tertiary laterite. In the central and northern parts of the area the plateau surface is represented by residual cappings of ferruginous duricrust and laterite above or near Archaean banded iron-formation. Such lateritic deposits commonly grade downslope into limonitic pisolite in benches fringing the hills, or in narrow, sinuous mesas standing about 50 m above the present alluvial plain. The pisolite is thought to have formed along watercourses on or below the Hamersley Surface.

Jutson (1950, p.64) assumed that the "Nullagine Plateau" was formed as a fairly level peneplain and that dissection was initiated by uplift and tilting towards the north. The height (a.s.l.) of the plateau surface decreases gradually northwards and northwestwards at a similar rate to that of present alluvial plains. Thus, although uplift relative to sea level must be responsible for dissection, there is little compelling evidence for a northerly tilt. The fact that the present drainage system is markedly asymetrical about the Chichester Range watershed can be explained by erosion of the Carawine Dolomite (Wittenoom Dolomite) in the Fortescue valley. Jutson (1950, p.62) considered that the Fortescue valley is a rift valley but Kriewaldt and Ryan (1967, p.22) disagreed, stating it to be "purely an erosional feature".

To the south of the Fortescue valley the Hamersley Surface is encountered at the top of a steep scarp, approximately 700 m a.s.l., that is, at a height compatible with the ancient peneplain at one stage having possessed a continuous northerly sloping profile across the present valley. A drainage system on such a peneplain would, following uplift, have commenced dissection close to the Indian Ocean. However, it seems highly probable that the west-northwest-striking outcrop of Carawine Dolomite in the position of the Fortescue valley would have been more rapidly eroded than the outcrops of Proterozoic banded iron-formations lying to the north and south of it. Headward erosion through the dolomite by strike-controlled subsequent channels could eventually have led to river capture from the west, creating the present valley. The width of the latter is governed by the outcrops of iron-formations to north and south. From Roy Hill homestead to Millstream homestead the river falls only 150-200 m over a distance of 330 km. This exceptionally low slope accounts for the river's poorly defined channel and sluggish flow during floods. Initially the Fortescue River appears to have flowed southwestwards from Millstream along the valley now occupied by the Robe River and Jimmawurrada Creek, but it was later captured by a river running through Gregory Gorge. Headward dissection from the west has been halted near Millstream by the resistance of the northerly iron-formation (Marra Mamba Iron Formation) which has produced a temporary base level. The scenic gorges around Wittenoom were formed by creeks flowing northwards off the Hamersley Range eroding rapidly downwards towards this base level, some 200 m below the level of the Hamersley Surface. According to this interpretation (which remains tentative), the pisolitic limonite and calcrete of the Fortescue Valley was deposited after early dissection of the peneplain. It is possible that pisolitic limonite of several ages may be present in the Pilbara.

DISSECTED PLATEAU

V-shaped valleys and gorges are widespread within the areas of dissected plateau. Many of the smaller creeks are joint-controlled, but on a regional scale drainage is dendritic. Where dissected plateau borders on plain country a prominent erosion scarp, in places about 100 m in height, exists. Similar scarps, though less marked, also occur where it meets range country.

The presence of deep valleys and gorges, locally containing waterfalls, and the general absence of soil cover establish that drainage development is in a juvenile stage; headward erosion southwards is still actively taking place. Between the watercourses the hill tops of the division represent isolated remnants of the Hamersley Surface and are of relatively constant height.

RANGE

Ranges of extremely rugged razor-backed hills and strike ridges, separated by narrow, steep-sided valleys are distinguished from dissected plateau by their different geomorphology. In fact the range and dissected plateau divisions have been formed in the same way, hill tops within the ranges being of fairly uniform height. Where remnants of the old plateau have survived, their edges are often marked by precipitous cliffs and waterfalls (dry, except during heavy rains).

Range country is confined to areas underlain by steeply inclined strata where erosion has preferentially removed the more readily weathered rocks; most of the ridges are composed of chert or quartzite. Comparison of Figure 1 with Plate 1 shows that most of the range division corresponds to outcrops of the Archaean layered succession; exceptions are steeply inclined Proterozoic rocks at Cape Preston and east of the Oakover valley. Drainage is generally strike-controlled, but water courses superimposed from the old plateau commonly cut across lithological boundaries with little deflection (e.g. Withnell Creek).

LOW GRANITE HILLS

Several parts of the area contain large expanses of almost completely bare granite, sometimes exposed in rugged hills but also forming traces of large "hump-back" hills. Individual hills are closely spaced in both types of country and are normally separated by only small sand plains littered with granitic rubble. The form of the hills is influenced by granite types present, porphyritic granite characteristically producing the hump-back variety, whereas sheared, jointed, well foliated and potassic types are weathered to form more rugged country.

The division constitutes a dissected peneplain, but in most cases this surface lies below the Hamersley Surface. Hickman and Lipple (1975) named it the "Intermediate Surface" and suggested that it may be equivalent to the "Peawah Surface" (Kriewaldt and Ryan, 1967) of the Pyramid Sheet area. In places (e.g. southwest from Coongan Belt mining centre and on the northeastern side of the Yilgalong Granite) the surface remains in its original, undissected form and is separated from the low granite hills division by a prominent scarp.

Between Goldsworthy and Shay Gap the division results from dissection of the desert surface which is considered to be essentially equivalent to the Hamersley Surface. The desert surface lies 100 m above the level of the De Grey River's alluvial plain and a steep scarp extends some 40 km parallel to and about 1 km to the south of the Shay Gap railway line. South from the scarp is a rugged granitic terrain possessing a juvenile drainage system.

PLAIN AND VALLEY

About 40 per cent of the area can be described as belonging to the "plain and valley" division. Most of the division occurs in the northern part of the area (Fig. 1) where peneplanation has reached an advanced stage. Apart from infrequent low outcrops of granite, dyke ridges, quartz reefs and scattered inselbergs, the plains are featureless, flat expanses of silty sand and gravel. All the plains are pediplains and have been formed by the progressive backward erosion of pediments into the rocks (generally granitic) which underlie them. Creek exposures and occasional granite platforms at plain level reveal that the sand and gravel deposits usually form only a thin veneer over solid rock. Drilling southwest of Goldsworthy has established that such superficial deposits are generally less than 40 m thick, even in areas of buried river channels. Farther inland the sand probably averages about 10 m in thickness.

It is notable that pediments rarely extend into Archaean or Proterozoic volcanic rocks. The scarp along the northern margin of the dissected plateau division from Mount Leopold to Bonnie Downs is retreating southwards by a process of undercutting. Archaean granite at the base of the scarp is eroded causing collapse of the overlying Proterozoic basaltic formations. Where the unconformity between the granite and the basalt reaches the level of the plain, backward erosion of the scarp appears to have halted.

That basaltic and granitic rocks are being weathered at different rates is exemplified by the presence of dyke ridges on the plains. Many of these ridges, generally only about 100 m in width but commonly tens of kilometres in length, rise up to 50 m above the surrounding countryside. At points where watercourses cross the dykes there are short gorges or water gaps, commonly containing pools or rock holes. Far longer gorges, often several kilometres in length, occur where rivers pass from plain country into range or dissected plateau; examples include Warrery Gap on the Coongan River, Shaw Gorge on the Shaw River, and a gorge 5 km west of North Pole mining centre, also on the Shaw River.

Not all areas of plain are underlain by granitic rocks. To the south and southwest of Mallina homestead the division occupies country underlain by Archaean sedimentary rocks, and in the Oakover valley underlying rocks include Permian and Proterozoic formations. The Phanerozoic geology of the Oakover valley proves that parts of the Pilbara Block were deeply eroded during the Palaeozoic. Permian glacial and fluvio-glacial deposits extend to depths in excess of 100 m below the plain, and deposits of similar age also crop out on the tops of neighbouring hills. This observation, coupled with the absence of other Palaeozoic deposits on the Pilbara Block, indicates that peneplanation responsible for the Hamersley Surface occurred over a long period of time, rather than being a strictly Tertiary phenomenon.

The nature of the superficial deposits covering the plain and valley division varies according to the geology of catchment areas. Rivers such as the Shaw, Yule and Turner which drain predominantly granitic terrain have developed sandy and pebbly alluvial flats, whereas rivers passing through basaltic country possess flood plains with large expanses of clay and fine silt.

DESERT

The eastern and northeastern margins of the area include the western edge of the Great Sandy Desert. Eolian sand forms predominantly flat country containing east-southeast-trending seif dunes and scattered rocky outcrops. The dunes are parallel, range in height up to 30 m and are spaced from 0.5 to 1.0 km apart. Spinifex covers the sand flats and the sides of the dunes; only the crests of the latter are still being reworked by wind action. Many of the dunes are asymetrical with steep southern slopes, and the crests are commonly braided or chain-like. Crowe (1975) classified and discussed the origin of sand dunes in the Great Sandy Desert.

Isolated seif dunes occur within the plain and valley division near Kangan and Mallina. Ryan (1966) noted that some of these dunes cover old drainage channels and that their encroachment has resulted in local drainage diversion.

COASTAL FLATLANDS

The coastal flatlands division is a low-lying tract of tidal mud flats, marshes and supratidal deposits of clacareous sand and clay. Much of the coastline is defined by sand dunes rising up to 20 m above the high tide mark. These dunes or sand ridges are composed of shelly beach sand and were obviously built by on-shore winds and/or wave action during storms. According to Gripp (1968) coastal sand dunes develop on stable and prograding shores. The dunes are breached by tidal creeks which drain the marshes, and are typically incised with steep banks up to 7 m in height.

North of the Ord Range the De Grey River has built a delta several hundred square kilometres in area. Drilling in the delta has revealed that the alluvial sediments are up to 100 m in thickness, yet the surface of the delta is now only about 10 m above sea level; this fact indicates local submergence during the history of the river. The geomorphology of the coastline at Dampier may also testify to submergence before more recent progradation.

PREVIOUS INVESTIGATIONS

REGIONAL GEOLOGY

In 1861, F. T. Gregory led an exploratory expedition across the region to establish its geography and suitability for pastoral activities. Gregory (1861 a and b) described much of the area as being composed of granitic rocks, originally capped by horizontal sandstone. Numerous "trap dykes" are said to have disturbed the surface of the country, "producing metamorphic rocks, some resembling jasper, and others highly cellular and scoriaceous".

In 1890 the Government Geologist, H. P. Woodward, investigated the western part of the Pilbara Block and prepared a report describing recent mineral discoveries and the geology of the Roebourne area. Woodward noted diorite at Cossack, ferruginous quartz rocks (sedimentary) near Roebourne, hornblende rock east of the Harding River, and farther east, granite. At Balla Balla "clay slate" was mentioned whereas to the north there are "amygdaloids" (presumably amygdaloidal basalt at Mount Negri). Woodward's traverse took him through country which he considered might be auriferous, to Croydon, Kangan Pool on the Sherlock River, where he crossed black hills composed of dolerite, and farther west across outcrops of sandstone near Pyramid homestead.

In the following year Woodward (1891) continued his survey, mapping "clay slate" at Egina and auriferous country at Pilbara flanked to the east by granite and to the west by ferruginous quartz. Immediately to the west of Nullagine, conglomerate rocks, probably of "Devonian" age, were said to contain reef gold. Eastwards from the town Woodward described "kaolinized slate" containing numerous quartz reefs. These strata (subsequently to be named the "Mosquito Creek Series") were said to extend 50 miles eastwards and a considerable distance in a north-south direction.

In 1894 Woodward presented a geological map of Western Australia which, in the Pilbara, drew a broad distinction between metamorphic rocks (greenstones and granite) and "Palaeozoic rocks" (equivalent to rocks now termed Proterozoic).

By 1896 the general distribution of granitic rocks and greenstones was fairly well appreciated (chiefly due to the efforts of prospectors) and Becher (1896) presented a sketch map of the Pilbara Goldfield. The map revealed that the country between the Coongan and Yule Rivers north of North Shaw was still largely unexplored. In a later paper Becher (1898) described a traverse from Condon (north of Goldsworthy) to Nullagine and mentioned belts of dolerite, diorite, schist, limestone, jasperoid quartzite, and actinolite rock between large plains underlain by granite. Becher referred to the conglomerate, grit, sandstone and slate west of Nullagine as the "Nullagine Beds".

Calvert (1899) summarized the area's geology in terms of a southern region of limestone and quartzite rocks, a northern area of alluvial plains with outcrops of granite and ironstone, and an intervening tract of country composed of sandstone, schist, slate, quartzite, conglomerate and "amygdaloids".

In 1896 the Geological Survey of Western Australia was established in its present form with A. G. Maitland being appointed as the Government Geologist. Maitland's investigations in the Pilbara Block during the early part of the twentieth century were recorded in three bulletins and made a major contribution to knowledge of the region's geology.

Maitland (1904) regarded the oldest rocks of the area to the granites and gneisses. Upon these rested the "greenstone schists and allied rocks including laminated, sometimes hematite-banded quartzites". The greenstones were considered to represent altered eruptive rocks and sedimentary rocks. The "Nullagine Beds" comprising sandstone, conglomerate, limestone and associated volcanic rocks, were considered to have been laid on top of the greenstone schists, probably during the Cambrian Period (although the age of these strata was said to be uncertain). Above the "Nullagine Beds", sandstone, limestone and chert were depositied, a sequence now preserved as the "Oakover Beds", in the vicinity of the Oakover River. The "Mosquito Creek Series" was first recognized by Maitland (1905, p. 10) who described it as a sequence of grits, shales and conglomerates in the area between Nullagine and Mosquito Creek. Maitland cited a locality (Garden Pool) near Nullagine where the unit is unconformably overlain by the "Nullagine Beds". This observation indicated that the "Mosquito Creek Series" is "Archean" (pre-Cambrian) in age. Maitland (1905) included a description of the Warrawoona area which was said to contain altered sedimentary rocks and metamorphic igneous rocks, possibly partly acidic in composition. He named this succession the "Warrawoona Beds"—part of the greenstone schists and of probable Archaean age. The "Warrawoona Beds" are intruded by granite, which farther south is unconformably overlain by the "Nullagine Beds". Two periods of basic dyke intrusion were recognized, the older suite having a northwest trend and the younger a northeast trend.

It should be noted that the stratigraphic nomenclature adopted at this time was rather flexible; for example, the "Nullagine Beds" were referred to also as the Nullagine "Series", and the "Mosquito Creek Series" was commonly called the Mosquito Creek "Beds".

Maitland (1906) established that the "Nullagine Beds" unconformably overlie the "Warrawoona Beds" at the Just-in-Time mine, near Marble Bar. In the reference to a coloured "Geological Sketch Map of the Pilbara Goldfield" (which appears as a frontispiece) he placed the "Mosquito Creek Series" above the "Warrawoona Beds", but presented no evidence for the relative ages of the two units. This map, which covered the area east of the Yule River, showed the distribution of all the units so far described at a scale of 1:633 600 (one inch to ten miles). It is reasonably accurate except in the southeastern part of the area, and was not significantly revised until 1957. In 1908 the three earlier bulletins were combined with some other material and reprinted as Bulletin 40 (Maitland, 1908). In Appendix 3 of this bulletin Montgomery stated that the oldest rocks in the Pilbara Goldfields were those belonging to the "Warrawoona Beds". Next in age were said to be the rocks of the "Mosquito Creek Series", followed by the granites and later dolerite dykes. Some of the latter may be related to the overlying "Nullagine Series". The "jasperiod quartzites" within the "Warrawoona Beds" were interpreted as silicified fault zones.

Maitland (1909) presented a geological sketch map of the western part of the Pilbara Block, based chiefly on a few traverses along the principal roads. As on his previous map of the east Pilbara, the general distribution of rock types was fairly accurately depicted. The bulletin included a map of the Roebourne area prepared by H. W. B. Talbot. This map distinguished serpentine rock, gabbro, dolerite, granite and allied rocks, volcanic rocks ("Nullagine Beds"), quartzite and conglomerate, and schist. Geological boundaries corresponded closely to those recognized today, except southwest from Mount Anketell. Maitland illustrated an unconformity beneath the "Nullagine Beds" at Station Peak and in the Pilbara-Hong Kong area, and correlated the conglomerate, grit and schist at Croydon with the "Mosquito Creek Series".

Another geological map of the west Pilbara was compiled by Woodward (1911). The oldest rocks of the area were considered to be the metamorphosed sediments ("Mosquito Creek Series") originally deposited in a marine, deep water environment. The greenstones were regarded as intrusive rocks, ranging from basic to ultrabasic composition. The map also showed banded chert, quartzite and ironstone units, but the cherts were not recognized as sedimentary.

Contributions by Maitland (1912) and Blatchford (1913) added little to the knowledge of the area's regional geology, but in 1915 Talbot presented a summary of mapping to the south of Nullagine, which indicated that Maitland's map of 1906 was incorrect south of latitude 22° S. A large area shown by Maitland as composed of granite was said by Talbot to contain lavas and sediments of the "Nullagine Beds". Talbot (1919, 1920) later expanded on his observations, presenting maps of the area south of latitude 21° 30′S. The "Nullagine Beds" were intermittently referred to as the Nullagine "Formation" and the Nullagine "Series", and were correlated with Ordovician rocks of South Australia. Talbot's maps showed the "formation" to occupy most of the area which he investigated, including large tracts of country in the Great Sandy Desert and south of Balfour Downs homestead. A mass of granite later to become known as the Gregory Range Granite (Noldart and Wyatt, 1962), was discovered along the Rabbit Proof Fence (approx. longitude 121°20′E) between latitudes 21°30′S and 22°10′S. In his 1919 paper Talbot described the "Paterson Range Series" for the first time. He described this unit as horizontally bedded sandstone unconformably overlying the "Nullagine Beds", and he thought it was of Carboniferous age. He also described the "Carawine Series", consisting of horizontally bedded dolomite which rests unconformably on the Nullagine Beds at a locality on Waltha Woora Creek. The dolomite was considered to be an estuarine deposit of uncertain age. Maitland (1919) placed the "Carawine Dolomite Series" within the "Nullagine Beds", and more recent investigations have proved him correct on this point.

Maitland's (1919) "A summary of the geology of Western Australia", published as part of Memoir 1, placed the "Warrawoona Beds", the "Mosquito Creek Series" and the "Nullagine Beds" in the Proterozoic System. The oldest rocks of the Pilbara Block were stated to be the "crystalline schists and allied rocks" which were Archaeozoic in age. These incuded greenstones and it is unclear from Maitland's account why the "Warrawoona Beds" were regarded as distinct from the crystalline schists. Fragments of laminated quartzite and jaspilite within conglomerate of the "Mosquito Creek Series" were cited as evidence that this unit is younger than the "Warrawoona Beds". Clarke (1923) correlated the "Warrawoona Beds" with the "Kalgoorlie Series" of the Yilgarn Block and suggested that the metamorphosed sedimentary rocks of the area may be equivalent to the "Yilgarn Series". The "Mosquito Creek Series", however, was said to be younger than the "Kalgoorlie Series" and older than the granitic rocks.

In 1930 Blatchford and Clarke published a geological map of Western Australia on which the greenstone belts of the Pilbara Block were shown as part of the "Kalgoorlie Series". A paper accompanying the map commented that E. S. Simpson, in a personal communication, agreed with Maitland (1919) that the "Mosquito Creek Series" is younger than the "Warrawoona Beds", but Blatchford explained that some of the strata mapped as belonging to the "Mosquito Creek Series" may in reality include representatives of the "Yilgarn Series"; other sedimentary units, likewise mapped, might be sedimentary facies equivalents of the "Kalgoorlie Series" or even part of the "Nullagine Beds".

David (1932) assigned the "Warrawoona Series" to the upper part of the Archaeozoic, the "Mosquito Series" to the "Older(?) Proterozoic", and the "Nullagine Series" to the "Newer Proterozoic". The "Warrawoona Series" was correlated with the "Kalgoorlie Series", and the "Mosquito Series" with the "Pine Creek Series" of northern Australia. Granitic rocks of the Pilbara were said to have been intruded after deposition of the "Mosquito Series".

Reports on numerous mining centres prepared by officers of the Aerial, Geological and Geophysical Survey of Northern Australia between 1935 and 1940 included maps showing the geological setting of the area's mineral deposits. Foreman's (1937) comment that Finucane working at the Eastern Creek centre, had discovered an unconformity between the "Warrawoona Beds" and the overlying "Mosquito Creek Series" (Finucane, 1939b, p. 18) illustrates that this work also added to knowledge of the Pilbara Block's regional geology.

Forman (1937), referring to the Precambrian succession of the Pilbara Block, stated that Maitland's generalizations of 1908 had been largely substantiated by subsequent work. The "Warrawoona Series" was said to contain the oldest recognizable rocks, consisting of basic and acid lava (locally pillowed), quartzite, carbonate-chlorite schist and chlorite-magnetite schist, steeply dipping with a prevailing northwest-southeast trend. Prider (1945, p. 53), reviewing the Precambrian of Western Australia, assigned both the "Warrawoona Series" and the "Mosquito Creek Series" to the Archaeozoic, but added that the stratigraphic succession of the "Warrawoona Series" was still unknown. He divided Archaeozoic granitic rocks of Western Australia into two groups: "(i) Older Granites belonging to an early period of granitization and granite intrusion under stress and (ii) Younger Granites of a later period of granite intrusion with which many of the State's metalliferous deposits appear to be genetically related"; but the subdivision was not extended to the Pilbara Block.

David (1950) in an account of the geology of Australia, accepted Maitland's stratigraphic subdivision and correlated all metavolcanic sequences in the Pilbara Block with the "Warrawoona Series", in which sedimentary rocks were said to underlie volcanics. The "Mosquito Series" was described only in the Mosquito Creek area. David found no clear evidence for the existence of "older" granites in the block and assumed that most are equivalents of the "later intrusions" mapped in the Yilgarn Block. The age of these granitic rocks was stated to be Middle or Upper Precambrian. He regarded the "Nullagine Series" as equivalent to the Upper Precambrian "Adelaide System" of South Australia. Conglomerate within the "Nullagine Series" was considered to be of fluvioglacial origin, but David correlated these beds with the "Braeside Tillite" (Clapp, 1925) of the Oakover valley, Clapp considered that the "Braeside Tillite" was pre-Jurassic and possibly of Permo-Carboniferous age.

Finucane (1953) and McMath (1953) assigned the "Nullagine Series" to the Proterozoic, and the "Warrawoona Series", "Mosquito Creek Series" and granitic rocks to the Archaeozoic. Prider (1954, p. 59-78) described the Precambrian geology of Western Australia but only briefly mentioned the Pilbara Block. Likewise, Sofoulis (1958c) repeated previous interpretations during a summary of the geology and mineralization of the "Nullagine Series" and "Mosquito Creek Series".

Traves and others (1956) accepted Maitland's (1905) concept of the block's stratigraphy, but assigned the "Warrawoona Series" and the "Mosquito Creek Series" to the Lower Proterozoic, chiefly on the basis of correlations with rocks of the Kimberley area. Their publication contains a geological map covering the Yarrie Sheet which shows a large area of Lower Proterozoic rocks in the Isabella Range. Previously this region was thought to contain granitic rocks and strata of the "Nullagine Series" (Maitland, 1919; Ellis, 1950), or granitic rocks and Permo-Carboniferous beds (Blatchford, 1933). Traves did not attempt a subdivision of the Lower Proterozoic rocks (chiefly "Warrawoona Series") "because of complex structure and indefinite lithological boundaries". Following mapping of the Marble Bar and Nullagine 1:250 000 scale Sheets by the Geological Survey in 1956 and 1957, Noldart and Wyatt (1958) reversed Traves' decision to move the "Warrawoona Series" and "Mosquito Creek Series" from the Archaeozoic to Proterozoic, and re-assigned both units to the Archaeozoic. West of Marble Bar, the "Nullagine Series" was said to extend to Pilgangoora and southwest to Dalton. Noldart and Wyatt distinguished two phases of deformation, a main phase producing northeast-trending folds, and subsequent cross folding about northwest-trending axes. They described the area's granitic bodies as being elongated north-northeastwards and associated with the main phase.

McWhae and others (1958) assigned the "Nullagine System" to the Upper Proterozoic, and the "Warrawoona System" and "Mosquito Creek System" were referred to as part of the "older Precambrian".

The Yarrie 4-Mile Geological Sheet (1:253 440) was published in 1959 with explanatory notes by Wells (1959) who stated that the "Braeside Tillite" is Permian and that it contains numerous striated pebbles and boulders.

Noldart (1960a) stated that the "Oakover Beds" unconformably overlie the "Braeside Tillite" and are Tertiary. The formation crops out in mesas, the tops of which are remnants of Jutson's (1950) "Nullagine Plateau". The same worker's investigation (Noldart, 1960b) of the Copper Hills copper mine resulted in the recognition of the Copper Hills Porphyry.

In 1962 the Geological Survey of Western Australia published Bulletin 115 (Noldart and Wyatt, 1962) describing the Marble Bar and Nullagine 1:250 000 scale Sheets. The "Warrawoona succession" and the "Mosquito Creek succession" were grouped into the "Pilbara System", with a sharp angular unconformity separating the two units. The "Warrawoona succession" was assigned to the Middle Archaean and the "Mosquito Creek succession" to the Upper Archaean. Five formations were recognized in the "Mosquito Creek succession", but three of these, the "Eastern Creek Formation", the "Dromedary Formation" and the "Gorge Creek Formation", were said to be equivalent in age and to form the basal sections of the succession in different areas. The "Middle Creek Formation" was said to be characterized by a high proportion of shale, slate and mica schist in sandstone and quartzite typical of the succession generally. Noldart and Wyatt (p. 103) commented on the fact that this formation carries the majority of auriferous deposits east of Nullagine. They noted that the "Budjan Creek Formation" is restricted to the district south of Copper Hills. Since this formation also unconformably overlies the "Warrawoona succession" it is not clear why it should have been regarded as younger than the other three basal units.

Noldart and Wyatt envisaged a complex history of tectonism and igneous intrusion. They described two principal phases of deformation affecting the area's Archaean rocks: the "Warrawoona orogeny" which predated deposition of the "Mosquito Creek succession" and produced the regional dome and syncline structures of the area, and the "Mosquito Creek orogeny" which caused east-west trending folding of the "Mosquito Creek succession". Granitic intrusion occurred mainly during the latter stages of the "Warrawoona orogeny", diapiric movement tightening pre-existing fold structures.

The "Nullagine succession" (Upper Proterozoic) was subdivided into a number of formations (Noldart and Wyatt, 1962, p. 66), but statements in the text make it clear that the tabulated sequence is not strictly chronostratigraphic.

Correlating metamorphosed sedimentary and volcanic rocks of the Warburton Range area with the "Nullagine System", Sofoulis (1962, p. 67) presented evidence to suggest that the latter might be of Lower Proterozoic age. The "Nullagine System" was considered to have been deposited in a "major north-west to south-east trending geosynclinal belt, marginal to the more primitive Archaean (Pilbarian-Yilgarnian) nucleus". This belt was considered to also extend southeastwards to Spencer Gulf in South Australia.

Ryan and Kriewaldt (1963) subdivided Archaean rocks of the area between Dampier and Roebourne according to lithology and stratigraphic position. Five rock units were distinguished in the following ascending order: (1) gneiss and granite, (2) amphibolite, ultrabasic rocks and acid lava, (3) chert and clastic sedimentary rocks, (4) basic volcanic rocks, and (5) banded iron-formation. This sequence was the first to be proposed since the three-fold division (Granite "Warrawoona Beds"—"Mosquito Creek Series") erected by Maitland (1905). Horwitz (1963) described lateral facies changes and a local unconformity in the same sequence northwest of Roebourne.

In the same year MacLeod and others (1963) subdivided the "Nullagine Series" of the Hamersley Range area into the Fortescue, Hamersley and Wyloo Groups. Subsequent mapping (Kriewaldt, 1964a; de la Hunty, 1965a; Ryan, 1966; MacLeod and de la Hunty, 1966; Kriewaldt and Ryan, 1967; Williams, 1968) established that Proterozoic rocks to the north of the Fortescue River belong chiefly to the Fortescue Group, which consists of a succession of basaltic lava flows (Mount Jope Basalt) conformably overlain by mudstone, sandstone, shale, chert and jaspilite (Jeerinah Formation) and underlain by the Hardey Sandstone. De la Hunty's (1963) mapping of the Balfour Downs Sheet slightly modified the stratigraphic interpretation of Proterozoic rocks made by Noldart and Wyatt (1962), but the previous terminology was retained. De la Hunty recognized a new stratigraphic unit in the Proterozoic succession, the "Manganese Group", which contains four formations; in ascending order these are the Coondoon Conglomerate, Bee Hill Sandstone, Balfour Shale and Noreena Shale.

In 1964 de la Hunty published Notes on the Balfour Downs Sheet but added little to his 1963 account of the area. Like Noldart and Wyatt (1962) de la Hunty considered that the Beatons Creek Conglomerate (base of the "Nullagine Series") is directly overlain by the "Tumbiana Pisolite".

Ryan (1964), Ryan and Kriewaldt (1964) and Kriewaldt (1964b) substantially reinterpreted the Archaean and Proterozoic geology of the Pilbara Block. Ryan redefined the "Pilbara System" as including not only Archaean volcanic and sedimentary rocks, but also the granitic rocks of the Pilbara Block. The system was thought to represent a single geosynclinal cycle which culminated in the "Pilbara orogeny" and associated granitic intrusion. In the West Pilbara Goldfield Ryan defined the "Roebourne Group" as composed of a lower clastic succession and an upper volcanic succession, although there is partial lateral equivalence by virtue of facies changes across the depositional trough. The unconformity between the "Warrawoona Series" and the "Mosquito Creek Series" in the eastern part of the block was considered to be of local significance only; both successions were correlated with the "Roebourne Group". Ryan suggested that the "Budjan Creek Formation" (Archaean according to Noldart and Wyatt, 1962) might belong to the Proterozoic Fortescue Group.

Ryan and Kriewaldt (1964) named the banded iron-formation near Roebourne the Cleaverville Formation, and underlying volcanic rocks, previously noted by the same authors in 1963, were termed the "Regal Formation". The Cleaverville Formation was tentatively correlated with banded iron-formation of the "Gorge Creek Formation". The clastic facies in the centre of the northeast-trending geosynclinal trough near Mount Satirist was estimated to be 13 km thick and said to comprise an upper assemblage of quartz sandstone, greywacke, shale, chert, jaspilite and amphibolite; a central assemblage of shale with calcareous and ferruginous beds; and a lower assemblage of shale, sandstone and greywacke. Greenstones and chert near the Pilbara mining centre were correlated with the upper and central sequences (i.e. equivalent to the Regal Formation).

De la Hunty (1965a) subdivided the Mount Jope Volcanics into three members: in ascending order the Boongal Pillow Lava Member, the Pyradie Pyroclastic Member and the Bunjinah Pillow Lava Member; the total thickness of the formation is about 2 000 m. During a description of manganese deposits at Woodie Woodie, de la Hunty (1965b) assigned the Carawine Dolomite to the Lower Proterozoic noting a correlation with the Wittenoom Dolomite (MacLeod and de la Hunty, 1966).

Kriewaldt (1964b) stated that the "Nullagine Series" in the Roebourne region is Lower Proterozoic in age (2 000 m.y.) and equivalent to the Fortescue Group. A newly recognised formation, the Mount Roe Basalt, forms the base of the group in this area. Other divisions of the Fortescue Group were recognised but not formally named. A 200 m thick basalt recorded between the Hardey Sandstone and the "Tumbiana Pisolite" was correlated with the lower part of the "Little De Grey Lava" (Noldart and Wyatt, 1962).

Low (1965) described the geology of the Port Hedland Sheet using the same stratigraphic subdivisions adopted by Noldart and Wyatt (1962). Low stated that the banded iron-formation at Goldsworthy is Archaean in age and, following Ryan and Kriewaldt (1964), correlated it with the "Gorge Creek Formation".

In 1965 the Geological Survey of Western Australia published a stratigraphic subdivision of the State's Precambrian rocks. The "Roebourne Group", "Warrawoona Beds" and "Mosquito Creek Beds" were equated and placed in the Archaean, whereas the Fortescue Group was designated Lower Proterozoic with an age of approximately 2 300 to 2 400 m.y. Prider (1965), however, maintained that the "Nullagine Series" is Upper Proterozoic with an age of 1 100 to 650 m.y. MacLeod and de la Hunty (1966) made a rather different subdivision of the Mount Jope Volcanics after mapping the Roy Hill Sheet. Here they stated that the basal member is the "Kylena Basalt Member", followed by the "Tumbiana Pisolite Member", and "Nymerina Basalt Member", the Kuruna Siltstone Member and the Maddina Basalt Member; the total thickness of the formation in this area was estimated at about 350 m. The Roy Hill Sheet succession has subsequently been recognized as the most applicable to the Pilbara Block as a whole.

Ryan (1965) interpreted the geology of the Pilbara Block using evidence acquired largely in the west Pilbara. The concept of a northeasterly elongated sedimentary trough between Whim Creek and the Pilbara mining centre was reaffirmed, a sequence of detrital rocks 12 km thick being envisaged. The upper part of this succession passes laterally northwestwards and southeastwards into volcanic rocks. The prevalence of major facies changes was stressed throughout Ryan's paper. Rocks of the Whim Creek area were correlated with the "Warrawoona succession" of the east Pilbara and regarded as entirely older than the "Mosquito Creek succession". The later was not correlated with the trough sequence (but see Fitton and others, 1975) which underlies the predominantly acidic succession of the Whim Creek area. Ryan noted numerous sedimentary structures in the sedimentary rocks of the trough, some of which revealed that part of the sequence was deposited from turbidity currents. The structure of the Pilbara Block was said to be dominated by large granitic domes between which the "Roebourne Group" is deformed by two directions of folding, one trending northerly and the other easterly. Cross folding about a northerly axis was considered to be responsible for local sinistral flexuring of the greenstone belts (e.g. at Mount Regal). Ryan said that the nature of the basement under the depositional trough and that of the source region for the detritus are unknown since no remnants are exposed; Brandt (1964, p.163) postulated granitic basement in the Mount Goldsworthy area. Ryan expressed the view that "acid igneous activity was concentrated at, though not restricted to, the junction between trough and shelf areas."

Horwitz (1966) compiled a geological map of Western Australia which collated evidence obtained during the 1:250 000 mapping programme of the Pilbara Block. The map made many important revisions and refinements to that presented by Low and Connolly in 1956, and its representation of the Pilbara Block remained essentially unchanged in a subsequent edition (Geological Survey of Western Australia, 1973).

Kriewaldt and Ryan (1967) recognized two new Proterozoic units on the Pyramid Sheet, the Cooya Pooya Dolerite and the Pillingini Tuff. The dolerite is a 100 m thick sill intruded along the contact between the Hardey Sandstone (locally referred to as the "Cliff Springs Formation") and the Kylena Basalt (upgraded from member), whereas the tuff conformably separates the Kylena Basalt from the Maddina Basalt (also upgraded from member). The Pillingini Tuff was tentatively correlated with the "Tumbiana Pisolite" which implied that the Nymerina Basalt wedges out between the Roy Hill and Pyramid Sheets.

Brown and others (1968) stated that the Granitic Complex of the Pilbara System probably includes the area's oldest rocks, an opinion previously voiced by Maitland (1908), Noldart and Wyatt (1962) and Brandt (1964), but clashing with the interpretation advanced by Horwitz (1966) who considered that all the area's granite intrudes the greenstones. Brown and others, like Kriewaldt (1964a, p. 7), compared the granitic masses to the "mantled gneiss domes" of Eskola (1949). They applied the term "Nullaginian System" to rocks of the Mount Bruce Supergroup, a practice previously criticized by Leggo and others (1965).

Williams (1968) named the lower part of the Roebourne Group the "Nickol River Formation", a unit later equated with the Warrawoona Group and the "Teichmans Group" (Fitton and others, 1975). Blockley (1971a) discussed the mineral resources of the Wodgina district and included a fairly detailed geological map showing the distribution of rock types and mines. He stated that the structure of the greenstone belt at Wodgina is that of a north-northeast-trending syncline on which drag folds and northwest-trending cross folds are said to be superimposed. Blockley considered that the syncline's position roughly corresponds to that of an Archaean depositional trough, since the thickest sequences of basalt and sedimentary rocks are now located in the axial region of the fold. One interesting feature of the paper is the recognition of finely layered ultramafic rocks which were interpreted as metamorphosed tuff. McCall (1971) described a succession of ultramafic and mafic sills in the Soanesville area. Various differentiation patterns were noted and it was concluded that the sills originated from a similar stem to the komatiites (Viljoen and Viljoen, 1969), perhaps of Geluk type.

Powell (1973) presented seismic data and the results of exploration drilling offshore from the Pilbara Block. The Pilbara Shelf, and extension of the Pilbara Block, was stated to terminate about 80 km from the coastline.

Lipple (1973) identified rhyodacitic pillow lavas near Soanesville and added that similar examples of this rather unusual rock type had been discovered elsewhere in the Archaean succession of the Marble Bar Sheet. Following a detailed investigation of the Mons Cupri area, Miller (1973) described stratabound lead-zinc and disseminated copper-zinc mineralization in rhyolitic rocks formed during the closing stages of volcanic activity in a eugeosynclinal environment. Rhyolitic fragmental rocks and laminated chert beds are underlain by 150 m of rhyolitic ash flow tuff with minor conglomerate and sandstone, and overlain by 180 m of dacite and andesite.

Hallberg (1974) conducted a petrographic and geochemical investigation of Archaean rocks from the Pilbara Block, intending to compare the area with the Eastern Goldfields Province. Surface weathering and carbonitization were found to be so extensive that only 28 of 369 specimens collected were analyzed. Hallberg concluded that alteration is generally so advanced as to render geochemical analysis futile, and commented that future geochemical studies in the Pilbara will be necessarily restricted to small areas or certain sequences or horizons. Donaldson (1974) described the layered ultramafic sequence of the Munni Munni Complex, 50 km south of Dampier. Rhythmic and cryptic layering, igneous lamination, pseudo-gravity stratification, slump structures and cumulus textures were identified and geochemical trends are said to be similar to those of the Skaergaard, Bushveld and Stillwater intrusions. Donaldson concluded that the Munni Munni Complex, first named by Williams (1968), is a single intrusion derived by differentiation of tholeiitic basalt.

During a description of fluorite deposits at Meentheena, 75 km east of Marble Bar, Hickman (1974) subdivided the Fortescue Group in a similar way to MacLeod and de la Hunty (1966) in their work on the Roy Hill Sheet; stratigraphic nomenclature used by Noldart and Wyatt (1962) was no longer applied. Two formations not present on the Roy Hill Sheet, the Mount Roe Basalt and the Hardey Sandstone, were identified by correlation with the succession of the west Pilbara.

Numerous reports on the geology of the Pilbara Block were published in 1975. The Marble Bar and Nullagine Sheets were remapped by the Geological Survey of Western Australia in 1972 and 1973, and Records (Hickman and Lipple, 1975, 1978; Hickman, 1975a, 1978) with accompanying geological maps were issued. Lithological subdivision was far more detailed than on previous maps and the Archaean layered succession was stratigraphically divided into two groups, three subgroups and twelve formations. Lipple (1975) formally defined these various stratigraphic units, noting correlations with previous subdivisions. At the same time, Hickman (1975b) provided a structural interpretation of the area covered by the Marble Bar and Nullagine Sheets. Five periods of deformation were recognized, the dominant structures (domes and synclines) originating during the second phase, D2. Hickman considered that the domes were formed by essentially solid-state uplift rather than by diapiric magmatic intrusion. It was also pointed out that the 15-30 km thick layered succession is broadly tabular on a regional scale and was not deposited in troughs positioned along the present greenstone belts.

Fitton and others (1975) presented a 1:250 000 stratigraphic map covering much of the west Pilbara and revised this area's stratigraphic succession. Earlier correlations between the western and eastern parts of the Pilbara Block (Ryan, 1965) were abandoned, chiefly because of Fitton's findings in the area around the Pilbara mining centre. Here they now mapped the "sedimentary succession" of Ryan's "Roebourne Group" as overlying the "volcanic succession". This discovery dispensed with the need to envisage rapid lateral facies changes between the thick Archaean volcanic and sedimentary sequences of the Pilbara Block. Fitton correlated the Archaean stratigraphic succession of the west Pilbara with that established farther east (Hickman and Lipple, 1975), but described a regional unconformity, intruded by basic sills over a wide area, which separates "Lower" from "Upper" Archaean rocks. Fitton and others were divided on the relative ages of the greenstones and the granitic rocks in the west Pilbara; Fitton and Sylvester favoured a pre-greenstone sialic basement, but Horwitz argued that the granitic rocks invariably bear an intrusive relationship to the greenstones.

Button (1975) stated that geologists working in the western part of the Pilbara Block had erected a five-fold stratigraphic subdivision of the Archaean layered succession. In ascending order the formations are: "Nickol River Formation", Cleaverville Formation, Negri Volcanics ("Regal Formation" of the Roebourne Sheet), "Mallina Greywacke" and "Croydon Sandstone". The Negri Volcanics were correlated with the Warrawoona Group of the east Pilbara. Tilloid (pebbly shale) was described from the "Mosquito Creek Group" at Eastern Creek, and Button commented that no angular unconformity is present between the Warrawoona Group and the "Mosquito Creek Group" at Cooke Creek; a conformable gradational contact was envisaged.

Gee (1975) noted three important differences between the Pilbara and Yilgarn Blocks: (1) as pointed out by Arriens (1971), granites in the Pilbara are generally about 400 m.y. older than those in the Yilgarn, and consequently the volcanogenic belts may be assumed to be older; (2) the oldest layered rocks in the Pilbara are volcanogenic whereas those in the Yilgarn are sedimentary; (3) Pilbara batholiths are approximately equant in plan, but those of the Yilgarn are markedly elongate. Gee concluded that crustal evolutionary processes operated differently in the two cratons.

Miller (1975) included Ryan and Kriewaldt's (1964) trough of sedimentation within the "Pilbara Eugeosyncline" which is said to have extended east-northeast from the Yarraloola Sheet to Port Hedland. The volcanic rocks on the northwestern margin of the trough were regarded as being of volcanic arc origin ("Pilbara Volcanic Arc"). Whim Creek, an area studied in detail by Miller, was positioned on the northern margin of the trough which contains a sequence of sedimentary rocks 15 km thick (a figure similar to that quoted by Ryan and Kriewaldt), whereas the volcanic pile is only 3 km thick. Most of the volcanic rocks are basaltic or andesitic but felsic rocks make up about 10 per cent of the succession. A lower sequence of volcanic rocks is isoclinally folded and overlain by an upper volcanic sequence which is essentially flat-lying. The contact between the two sequences is intruded by ultramafic rocks and the entire pile is underlain by the arc's oldest rocks, granitic gneisses.

Miller related the Archaean volcanic and sedimentary rocks of the east Pilbara to the "Kalgoorlie-Marble Bar Eugeosyncline". No arguments were presented for the existence of this structure other than the observation that the rock types of the east Pilbara are typical of eugeosynclines.

Blockley (1975) stated that the oldest rocks of the Pilbara Block are volcanic and sedimentary sequences deposited in troughs between massive crustal blocks.

Rutland (1976) presented a résumé of recent work on the Pilbara-Yilgarn province during an account of the orogenic evolution of Australia. Problems discussed included the respective ages of greenstones within the Pilbara and Yilgarn Blocks and the nature of the basement on which the greenstones were deposited.

Ingram (1977) presented a stratigraphic subdivision of Archaean rocks in the east Pilbara; the same subdivision was originally proposed in unpublished form as early as 1972. Four Lower Archaean formations and one Upper Archaean unit were named in the following ascending order: "Chocolate Hill Formation", "Sharks Formation", "Miralga Formation", "Gorge Creek Formation", and "Mosquito Creek succession". The lowest formation is characterized by a high proportion of ultramafic rocks (including high-magnesium basalt of the komati type), the upper two formations by sedimentary rocks, and the central formations by mafic and felsic volcanic rocks. The succession, described as geosynclinal, was said to exceed 13 km in thickness and was considered to have been deposited on a gneissic basement. Cyclicity was recognized in the volcanic formations and three classes of ultramafic intrusion were described: volcanogenic (most significant with respect to nickel mineralization), layered, and orogenic.

Hickman (1977d) discussed the geology of the Whim Creek area, presenting a different stratigraphic interpretation to that given by Fitton and others (1975). Two formations, the Mallina Formation and the Constantine Sandstone both previously included in the Whim Creek Group (Fitton and others, 1975) were now assigned to the Gorge Creek Group. The regional unconformity recognized by Fitton was not substantiated. Hickman (1977c) further subdivided the Warrawoona Group, formally naming and defining many of the units previously noted by Lipple (1975). Urban Geology Series 1:50 000 scale geological maps and reports on resources for parts of the west Pilbara Block have been prepared by the Geological Survey of Western Australia.

ECONOMIC GEOLOGY

The first discovery of gold in the Pilbara Block may have been made in 1688 by William Dampier (Woodward, 1890, p.22) who named part of the area "Provincia Aurifera". If Dampier did find gold, it appears to have been in small quantities, because the area remained untested for a further two hundred years.

Copper was discovered near Roebourne in 1872 and auriferous quartz reefs yielding about 170 g/t of gold (Maitland, 1909) were discovered close to the township in 1877. In 1882 a 435 g nugget of gold was found between Cossack and Roebourne, and in 1886 a prospector, Mr N. W. Cook, found gold at Nullagine (Becher, 1898, p.47; Maitland, 1905). In 1888 gold was found at Mallina and interest in the Pilbara was aroused. Rich alluvial gold deposits were subsequently discovered near Pilbara Well in July 1888, one nugget weighing 3.95 kg, and the Pilbara Goldfield was proclaimed a few months later. The ensuing gold-rush rapidly uncovered many more areas containing gold, antimony, copper, tin, lead, iron, asbestos and diamonds.

Woodward (1890) described mineral discoveries in the western part of the Pilbara Block, and commented on clay slate with a large gossan cap near Balla Balla (Whim Creek deposit). In the following year Woodward (1891) described auriferous country around the Pilbara mining centre, and conglomerate at Nullagine was said to contain reef gold. East of Nullagine, Woodward considered that there was "a very nice patch of auriferous country" (Mosquito Creek Formation). Woodward also reported discoveries of gold at Nickol River, tin at Pilbara and tin on the Shaw River (near Hillside). He concluded that "the North-west district as a whole is rich in minerals; wherever the slates occur gold is found, and wherever the granite outcrops prospects of tin may be obtained, and also mica of the first class quality". Becher (1896) referred to individual mining centres in the region, adding various comments about their local geology. In 1898 Becher described gold diggings at Nullagine and mentioned a discovery of diamonds near the town.

During a description of gold-mining centres Calvert (1899) commented that the "Marble Bar field lies in a nest of low sandstone and slate hills to the east of the Coongan River. No field that I have visited, and no district of which I have studied the report, appears to me to hold out more brilliant prospects for the future".

Maitland (1904, 1905, 1906) and Woodward (1911) gave detailed descriptions of many mining centres in the Pilbara Block. Maitland (1909) commented that cassiterite at the Pilbara mining centre was derived from pegmatite dykes at a granite contact with basic rocks. Maitland (1919) presented a summary of the area's mineral potential, especially with respect to gold, tin, copper and antimony. Iron ore was said to be plentiful, laminated quartzite and jasper veins passing laterally into bodies of virtually pure hematite.

Reports on various mining centres and mineral occurrences were presented by Blatchford (1921, 1925), Simpson (1922), Wilson (1922, 1925), and Simpson (1928). From 1935 to 1940 an exhaustive survey of mining centres in the Pilbara Goldfield was undertaken by officers of the Aerial, Geological and Geophysical Survey of Northern Australia (AGGSNA). The resulting 41 reports on the Pilbara still constitute a useful source of reference for anyone interested in the economic geology of individual mines, centres or districts within the block. A later series of reports by members of the Geological Survey of Western Australia (Rowledge, 1944; Ellis, 1945a,b,c; Forman, 1945; Ellis, 1950) was concerned chiefly with deposits of pegmatite minerals.

Simpson (1948, 1951, 1952) presented a comprehensive account of mineral occurrences in Western Australia mentioning many localities in the Pilbara Block.

In 1955 de la Hunty described the Mount Sydney manganese deposits, and in 1958 Sofoulis (1958b) discussed the occurrence of diamonds at Nullagine. De la Hunty (1958a) subsequently described manganese deposits at Woodie Woodie, confirming that the dolomite host rock is part of the "Nullagine Series" (cf. Talbot, 1919).

Connolly (1959) assessed the iron ore potential of Western Australia. In the Pilbara Goldfield the hematite deposits of Mount Goldsworthy were said to consitute economic ore bodies, but magnetite deposits near Andover were said to be low grade and to possess a high titanium content.

Further reports on mineral deposits were published by de la Hunty (1958b, 1960, 1961a,b), Low (1960a,b,c; 1961), Sofoulis (1960a,b) and Ellis (1962). The work by Low and Sofoulis at Bamboo Creek established the continuation of gold mineralization to depths in excess of 100 m; one diamond drill hole intersected a 1.1 m wide quartz vein averaging 300 g/t (almost 10 oz. per ton). Drilling at Mount Goldsworthy (Low, 1961) revealed 25 Mt of hematite ore (Fe content 60-65 per cent) in the main deposit, and de la Hunty's investigation of several Tertiary limonitic deposits south of Port Hedland enabled him to estimate total reserves at 18 Mt of ore ranging from 53 to 57 per cent Fe (60 to 64 per cent Fe after beneficiation).

Low (1963) and de la Hunty (1963) presented detailed descriptions of Western Australia's copper and manganese deposits respectively. De la Hunty's main contribution was to recognize a "Manganese Province" in the Pilbara in which a particular sequence of Proterozoic sedimentary strata, the "Manganese Group" (now

Manganese Subgroup) formed protore for subsequent Tertiary supergene enrichment. Shale formations contain up to 13.2 per cent Mn and the underlying Carawine Dolomite contains up to 2.9 per cent Mn. Numerous pellets of braunite occur in the Noreena Shale.

In reference to the Mount Goldsworthy iron ore deposits Low (1965) commented that the estimate of total ore reserves was then 65 Mt of 54 to 64 per cent hematite and hematite-goethite ore. Detailed descriptions of the Goldsworthy iron ore deposits were provided by Brandt (1964, 1966), and Matheson and others (1965).

De la Hunty (1965b) and Rowston (1965) discussed the manganese deposits of the area around Woodie Woodie and Mount Sydney. The Pinjian Chert Breccia, which unconformably overlies the Carawine Dolomite, and is intimately associated with the manganese deposits, was said to be of Upper Proterozoic age. It was also concluded that the deposits at Woodie Woodie were not formed by supergene enrichment of manganiferous sediments. Discussing ore genesis in the Pilbara, Ryan (1965) commented that economic mineral deposits in the West Pilbara Goldfield are concentrated in the middle of the "Roebourne Group" and probably represent secondary concentrations derived from the rocks at this particular stratigraphic level.

Blockley (1970) concluded that the cassiterite deposits of the Pilbara Block are associated with a particular type of relatively late granitic rock. Pegmatite dykes fringing certain plutons have been weathered to produce secondary concentrations in alluvial and eluvial deposits. The "tin granites" are biotite adamellite, seldom foliated (in contrast to most of the block's granitic rocks), and crop out in tors or smooth, exfoliated domes. Blockley (1971b) presented a bulletin on the lead, zinc and silver deposits of Western Australia which includes accounts of the Braeside lead field and relatively minor occurrences in the Pilbara and West Pilbara Goldfields.

Hickman (1973) described sedimentary barite deposits at North Pole which are situated near the centre of a large dome deforming an Archaean succession of pillow basalt, chert, felsic lava and minor sedimentary rocks.

In a joint paper Miller and Gair (1975) discussed the copper-lead-zinc-silver deposits at Mons Cupri. As Miller (1975) pointed out, the deposits are associated with rhyolitic pyroclastic rocks and siliceous hot spring sinters within the upper volcanic succession of the arc. Reynolds and others (1975) described the volcanogenic copper-zinc deposits of Marble Bar (Big Stubby), Whundo and Whim Creek; all are associated with acid volcanics and sedimentary rocks. Miller and Smith (1975) discussed the geology of the nickel-copper deposit at Sherlock Bay. The ore body is located in a banded quartz-amphibole-magnetite-sulphide rock which was interpreted as occupying a fault zone. Nickel was thought to have been derived from a nearby ultramafic body. In the following year Blockley (1976) described recently worked deposits of tiger-eye in the Ord Range, commenting that this is the only known occurrence of crocidolite in an Archaean banded iron-formation.

Marston (1979) presented a comprehensive account of copper deposits in the Pilbara block as part of a description of copper mineralization in Western Australia. The bulletin constitutes a major revision of a previous edition by Low (1963). Apart from updating production statistics and reserve estimates, Marston was able to classify the deposits according to geological setting and the nature of the ore. Blockley (1980) has compiled a bulletin on the tin deposits of Western Australia in which the Pilbara Block figures prominently. Baxter (1978) describes tungsten, chromium, molybdenum and vanadium mineralization in the area.

GEOCHRONOLOGY

Simpson (1912) analyzed mackintoshite, thorogummite and pilbarite from Wodgina, and computed an age for the pilbarite of 13 m.y. based on an estimate of the helium present; this result may represent a weathering age.

Cotton (1926) dated fergusonite from pegmatite near Cooglegong at 620 m.y. and mackintoshite, thorogummite and pilbarite from Wodgina at 1 475, 1 460 and 3 840 m.y. respectively. A year later Holmes (1927) reported a similar age of 1 260 m.y. for mackintoshite from Wodgina, probably using Simpson's (1912a) data.

Greenhalgh and Jeffery (1959) revised earlier work of Jeffery (1956) to arrive at Rb-Sr ages of 2 930 m.y. on muscovite and 2 840 m.y. on microcline from a pegmatite body at Wodgina, and a U-Pb age of about 2 600 to 2 400 m.y. on tanteuxenite from a locality south of Woodstock. These determinations constitute the first reliable geochronological data from the Pilbara Block, and confirmed its Archaean age.

Leggo and others (1965) used Rb-Sr isotope analysis to deduce a maximum age of 3 040 m.y. for a sample of granite, collected 1.5 km northeast of Moorambinar Pool. Since only one rock sample was studied the reliability of this result as a true indication of age is rather low; microcline from the same specimen yielded an age of 2 290 m.y., but Leggo explained that this "Proterozoic" age is probably due to a post-emplacement rearrangement of radiogenic strontium. Leggo also quoted a written communication from Riley to the effect the lepidolite from the Wodgina pegmatite dated by Greenhalgh and Jeffery (1959) had yielded an age of 2 910 m.y.

Further geochronological data on the granitic rocks of the area was provided by Compston and Arriens (1968). Twelve samples of granite from various batholiths gave a Rb-Sr isochron of 3 050 ± 180 m.y. Four of these twelve samples came from the southern part of the Mount Edgar Batholith, and de Laeter (pers. comm.) has recently used their isotopic ratios to yield an age of 3 279 ± 169 m.y. (R_i 0.702 6 ± 0.001 9). This represents the oldest Rb-Sr age yet obtained from the Pilbara Block. Compston and Arriens (1968) reported ages of 3 000 m.y. for acid lavas from Whim Creek, 2 190 ± 100 m.y. for acid igneous rocks from the Jeerinah Formation at the top of the Fortescue Group, approximately 2 200 m.y. for pisolitic tuff near the base of the Fortescue Group, and 2 940 m.y. for muscovite (probably detrital) from the "Cliff Springs Formation".

In 1970 de Laeter and Trendall dated the Copper Hills Porphyry at 2 880 ± 66 m.y. using the Rb-Sr method. As noted by Noldart (1960b), the porphyry intrudes the Warrawoona Group which must therefore be older than 2 900 m.y. In the following year de Laeter and Trendall (1971) obtained a Rb-Sr age of 2 196 ± 26 m.y. for the Gidley Granophyre which intrudes the Proterozoic/Archaean unconformity in the Dampier area.

McCall (1971) and Arriens (1971) commented that the discrepancy between the apparent ages of the "Kalgoorlie-Yilgarn and Pilbara systems" may reflect metamorphic superimposition of younger ages in the former; Pilbara granites are generally 3 000 m.y. old whereas most of the granites in the Yilgarn Block have yielded ages of about 2 600 m.y.

De Laeter and Blockley (1972) reported ages of 3 125 ± 366 m.y. (recently recalculated to 3059 ± 358 m.y.) for granitic migmatite and 2 670 ± 95 m.y. (recalculated to 2 614 ± 93 m.y.) for "tin granite" at Moolyella. Initial $^{87}Sr/^{86}Sr$ ratios suggested that the older granite is close to primary crustal material, and that the later intrusion ("Moolyella Granite") consists of reworked material, probably formed by partial melting of the older granite. The "Moolyella Granite" has a significantly younger age than any previously recorded from a granite within the Pilbara Block and this established two phases of intrusion.

Arriens (1975) stated that the published 3 000 m.y. age for acid lavas at Whim Creek may require revision, but gave no new interpretation. Fitton and others (1975), however, quoted a personal communication from Arriens suggesting an age range between 2 500 and 2 300 m.y.

Lewis and others (1975) dated the Black Range dolerite dyke at 2 329 ± 89 m.y., an especially significant result since they considered it to be a probable feeder of the lowest formation of the Fortescue Group, the Mount Roe Basalt. De Laeter and others (1975) reported two radiometric ages from the Shaw Batholith. The older age (probably metamorphic) from migmatite and gneissic granitic rock, was 2 951 ± 83 m.y. (recalculated to 2 889 ± 81 m.y.), and a post-tectonic granite, the Cooglegong Adamellite, was dated at 2 606 ± 128 m.y. (recalculated to 2 551 ± 125 m.y.).

Further geochronological data on granitic rocks of the Pilbara Block was provided by Oversby (1976) who dated samples from seven localities using both the Pb-Pb and Rb-Sr methods. Four of the localities show isotopic evidence of metamorphism at 2 950 m.y. and it was suggested that this represents the age of doming in granitic rocks of the east Pilbara. Two of these localities reveal effects of post-tectonic metamorphism at 2 700 to 2 600 m.y. and the other three localities underwent metamorphism as late at 2 250 to 2 000 m.y. Oversby suggested that this last event may be associated with Proterozoic volcanic activity responsible for deposition of the Fortescue Group.

Additional geochronological information is included in papers by Hickman and de Laeter (1977) and de Laeter and others (1977). The former of these contributions employed geochemical data to confirm field evidence that the Hardey Sandstone (Fortescue Group) is of freshwater origin, and the Rb-Sr method was used to date the unit at about 2 650 m.y. The reliability of this result was critically examined since, if it is a true reflection of the formation's depositional age, the Proterozoic/Archaean unconformity in the Pilbara Block must be of greater antiquity than previously supposed. De Laeter and others (1977) dated the Cooke's Creek Granite at 2 600 m.y. and granitic rocks from Lookout Rocks at 2 651 m.y.

Richards (1978) measured lead isotope ratios for samples of galena from veins and faults at six localities in the Pilbara region. Lead from Doolena Gap mine was dated at 3 340 m.y. This material was collected from a quartz vein intruding Archaean metasediments and ultramafic rocks stratigraphically close to the level of the Marble Bar Chert Member. This age agrees quite well with a zircon U-Pb age of 3 453 ± 16 m.y. obtained by Pidgeon (1978a) on dacite from the Duffer Formation (slightly lower in the succession) at a locality 27 km southwest of Marble Bar. Other results obtained by Richards from galena collected in the Pilbara Block and its environs are 2 510 to 2 420 m.y. from a quartz vein within the Cooglegong Adamellite a few kilometres north of Hillside, 2 010 to 1 760 m.y. from Andover mine, 2 350 to 2 080 m.y. from Flat Rock mine, and 2 740 to 2 670 m.y. from the Braeside lead workings (2 samples). The last result conflicts with the fact that the lead at Braeside occurs within rocks of the Fortescue Group, for a long time considered to be about 2 400 m.y. old.

Sangster and Brook (1977) dated lead from the Big Stubby zinc-lead-barite deposit (5 km south of Marble Bar) at 3 500 m.y. using the Pb-Pb method. This result agrees closely with the zircon date obtained by Pidgeon (1978a) from the same formation 26 km to the southwest.

Pidgeon (1978b) has obtained zircon U-Pb dates of 3 417 ± 40 m.y. on migmatite from Canning Tin (Shaw Batholith) and 3 280 ± 20 m.y. on homogeneous granite from the Moolyella area (Mount Edgar Batholith), and reported a Rb-Sr age of 2 830 ± 30 m.y. on muscovite from tin-bearing pegmatite associated with the post-tectonic granitic intrusions. J. R. de Laeter (pers. comm.), has determined a provisional Rb-Sr age (pending further isotopic analyses) of 2 915 ± 207 m.y. for granodiorite and porphyry at Coppin Gap. More recent geochronological data are summarized by Hickman (1981).

CHAPTER 2

Archaean

The Archaean geology of the block is, in most respects, similar to that of Archaean shield areas and cratons elsewhere in the world (e.g. Barberton Mountain Land, South Africa). Granitic rocks, which constitute approximately 60 per cent of the block, range in composition from alkali feldspar granite to tonalite, and form domal batholiths composed of numerous separate intrusions. They fall into three main categories: (1) a migmatitic, gneissic and foliated complex, metamorphosed approximately 3 000 m.y. ago; (2) porphyritic adamellite and grandiorite; and (3) post-tectonic granite and adamellite plutons and stocks, intruded 2 700 to 2 600 m.y. ago. The third of these categories is economically most important because of its associated tin deposits.

The granitic domes are separted by synclines containing volcanic, sedimentary and intrusive rocks, previously referred to as the "greenstones" or "layered succession" but now named the Pilbara Supergroup. The shapes of these synclines are irregular, and are controlled by the positions of adjacent granitic batholiths (Plate 1B). The Pilbara Supergroup varies in thickness across the area because of local unconformities, tectonic modification, mafic to ultramafic intrusive complexes and granitic intrusion at its base. In most districts, however, it exceeds 10 km in thickness (Plate 2) and is composed of two major stratigraphic units; (1) the Warrawoona Group, a predominantly volcanic assemblage of mafic, felsic and ultramafic rocks, with subordinate chert; overlain by (2) the Gorge Creek Group, a predominantly sedimentary sequence of sandstone, conglomerate, greywacke, shale and banded iron-formation, with subordinate basalt and gabbro. In the west Pilbara an upper volcanic unit, the Whim Creek Group, unconformably overlies the Gorge Creek and Warrawoona Groups.

GRANITIC ROCKS

Although only six categories of granitic rock are shown on Plate 1A, the variety of rock types and number of individual plutons in the Pilbara Block is considerably greater. The principal batholiths, many containing several intrusions, form structural domes between which the layered succession is deformed into deep-rooted synclines and synclinoria. Plutonic boundaries within the batholiths can generally be recognized using compositional and textural criteria, intrusive relations and photogeological interpretation. In some cases, however, post-intrusive tectonic deformation has obscured original relationships.

The origin of the domes and their temporal relations to the layered succession are much debated. Field evidence and geochronological studies establish that many of the intrusions are younger than the oldest parts of the layered succession, but structural criteria (discussed later) prove that a large part of the granitic complex existed prior to the main episode of doming. It is possible that the batholiths include remnants of an early sialic basement, on which deposition of the Talga Talga Subgroup (Table 2) commenced about 3 500 m.y. ago. Alternatively the Talga Talga Subgroup may be the oldest crustal material preserved.

The following pages discuss the main categories of granitic rock before describing the geology of individual batholiths and plutons.

FOLIATED, GNEISSIC AND MIGMATITIC ROCKS

Granitic rocks compositionally close to the mineralogical boundary between adamellite and granodiorite (i.e. about twice as much plagioclase as potash feldspar) make up the greater part of the area's batholiths. Most of the rocks are well foliated, although the degree to which foliation is developed depends chiefly on structural environment; rocks near batholith margins are far more strongly foliated than those in the centres of domes. Likewise, whether the rocks are homogeneous, migmatitic, agmatitic or gneissic is governed by local geological setting rather than age. The greater parts of the batholiths are neither conspicuously migmatitic, gneissic or sheared, but contain moderately well foliated, equigranular rock. Exposure is generally quite poor, and outcrops are restricted to scattered inselbergs, occasional rock platforms at plain level, and numerous isolated, rounded crags, often no more than a few metres in height. The rock weathers to adopt a pale reddish-brown appearance but fresh rock is typically mottled grey. Deep weathering is uncommon and visible alteration rarely extends more than 50 mm beneath the surface.

The principal foliation is generally a biotite alignment, but quartz, feldspar and mafic minerals may exhibit parallel orientation. Generally this foliation is of tectonic origin rather than a flow feature produced during intrusion and consolidation, and it

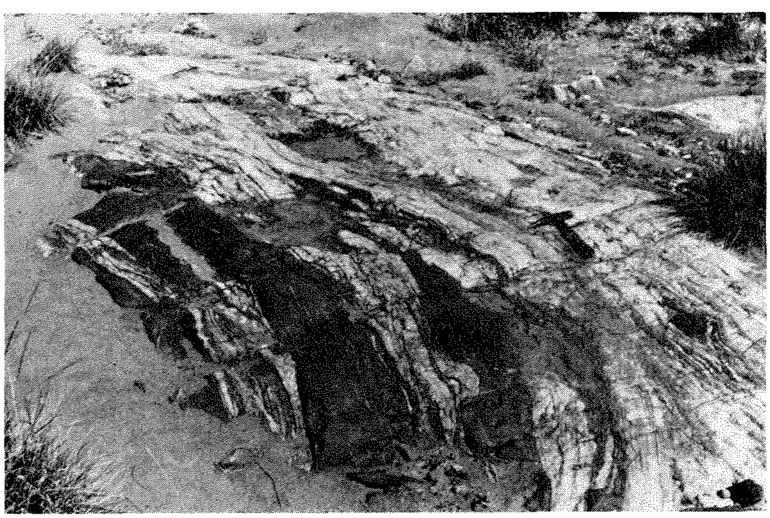

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Figure 2. Banded migmatitic gneiss exposed in the Shaw River 8 km west of Spear Hill. The amphibolite palaeosome (dark) was probably stoped from the North Shaw Belt, 2 km to the west. The granodioritic material at this locality is dated at 2 951 ± 83 m.y. (de Laeter and others, 1975) and 2 936 ± 9 m.y. (Oversby, 1976). Both these results probably mark the last major metamorphic event (ca. 2 950 m.y.).

commonly continues uninterrupted across intrusive contacts. At a few localities it is demonstrably axial planar to folds generated within gneissic or pegmatitic units. On a regional scale the foliation is broadly concentric within the domes and parallel to their contacts with the layered succession.

Fine to coarse, even-grained biotite adamellite, biotite granodiorite and, less commonly, biotite tonalite form migmatite adjacent to the greenstone belts and in isolated areas within the batholiths. Stromatic, agmatitic, nebulitic and gneissic varieties are represented but subdivision would require a more detailed study. Banding is exhibited as wisps, schlieren and layers of mafic or ultramafic palaeosomes (Figure 2). Where accompanied by leucosomes of aplite and pegmatite intruded along the foliation, these mafic layers produce a pronounced striped appearance. Textural changes may be gradual or abrupt, and banding straight or contorted. Migmatite close to greenstone contacts is almost certainly syntectonic, formed by lit-par-lit injection and rafting during the doming process. Geochronology (e.g. de Laeter and others, 1975) suggests that such units are about 3 000 m.y. old, but bodies of migmatite farther within the batholiths may well be older and related to reworking of early crustal material.

Blockley (1980) considers that the oldest rocks in the Moolyella area of the Mount Edgar Batholith are of gneissic and foliated granite which intrudes the Warrawoona Group, and that the contact is marked by a zone of migmatite 1 km wide. In places the gneissic granite contains rafts of altered gabbro or irregular inclusions of amphibolite, but in general it ranges from tonalite to adamellite. Near the Moolyella tin workings this mass is said to be intruded by foliated granite which contains blocks of the migmatite.

Remobilized migmatite crops at Mulgandinnah Hill, southeast of Hillside, near Woodstock, and at Coorong Creek. The Mulgandinnah Adamellite intrudes the surrounding migmatitic complex, and has diffuse boundaries across which the biotite foliation passes without interruption.

Another variety of the foliated category of granitic rock is sheared adamellite. Examples occur in the Yilgalong Granite, the Kurrana Batholith, the Gregory Granitic Complex, on the eastern side of the Shaw Batholith, and in the Chiratta and Karratha Batholiths. In most areas the rock is visibly sheared, locally to the point of being flaggy or platy, and augen structures are numerous. Microscopic examination invariably reveals strain, cataclasis (including mylonitization) and neocrystallization.

The only detailed petrographic study of granitic rocks in the Pilbara Block is that carried out by Blockley (1980) on the various tin fields. Essential minerals of the granitic complex are generally quartz, plagioclase, microcline, biotite and hornblende (comparatively rare); accessory minerals are chlorite, epidote, sphene, apatite, zircon and magnetite. Biotite is commonly altered to chlorite; hornblende to chlorite, carbonate and epidote; and plagioclase to sericite. Palaeosome and neosome alternate in migmatite producing sudden changes in mineralogy over a few centimetres. Metamorphism has modified the original granitoid character of the rocks to produce granoblastic, lepidoblastic, protoclastic or mylonitic fabrics.

MIGMATITE WITH LARGE GREENSTONE XENOLITHS

Tracts of country in which granitic rocks contain a large proportion of greenstone xenoliths, are interpreted as contact zones at batholith margins, or root zones occupying synclinal belts within the domes. Some xenolith-rich zones within the batholiths, which cannot be directly related to the main greenstone belts (i.e. with no obvious structural connection), may represent ancient migmatite formed by granitic injection of very early greenstone units (pre-Talga Talga Subgroup). The composition of granitic rocks of this category is typically granodiorite or tonalite, probably partly because of assimilation of mafic material from the greenstones. Amphibolite facies metamorphism and shearing are common.

GRANODIORITE AND TONALITE

Intrusions of grandiorite to tonalite composition are distinguished (Plate 1A) near Marble Bar, North Shaw, Abydos, Strelley, Mount Gratwick, Peawah and west of Cooya Pooya. The rock is commonly well foliated and rich in biotite and hornblende, but the intrusions at Mount Gratwick and North Shaw are exceptions to this generalization. Composition is variable due to the assimilation of mafic material from the layered succession, and a notable feature of this type of rock is its prevalence near batholith margins, where greenstone inclusions are most numerous. Northeast of Abydos three small plutons of grey, fine-grained, well-foliated biotite granodiorite intrude greenstones of the Pilgangoora Syncline, and small stocks of granodiorite intrude the Warrawoona Group west of Cooya Pooya homestead. The rock is fine to medium grained, locally porphyritic and generally quite deeply weathered.

The mineralogy of the rocks in this category is typical of that encountered in granodiorite and tonalite. Oligoclase is the main rock-forming mineral, but variable amounts of quartz, microcline, biotite and hornblende occur. Metamorphism is accompanied by the development of muscovite and chlorite; sericite and epidote are common secondary minerals. Accessory minerals include sphene, apatite, zircon, allanite and opaques.

PORPHYRITIC ADAMELLITE AND GRANODIORITE

Seventeen masses of porphyritic adamellite and granodiorite are shown on Plate 1A. This category mainly contains rocks intermediate in age between the migmatite and granodiorite complex and the post-tectonic granites, but some of the bodies may represent phases of the latter. Blockley (1980) has suggested that the porphyritic rocks immediately east of Wodgina are part of the post-tectonic Numbana Granite, the main body of which lies farther to the south. As yet only one of the porphyritic plutons has been dated (40-Mile Quarry, Oversby, 1976) but intrusive relations indicate that most are between 3 000 and 2 700 m.y. in age.

The commonest medium- to coarse-grained biotite adamellite contains numerous euhedral phenocrysts of microcline up to 30 mm in length. In many cases these phenocrysts exhibit a pronounced alignment parallel, or subparallel, to the biotite foliation. Hornblende is an important constituent in some intrusions, and gives the rock a speckled appearance. The rock is generally well foliated, and, near batholith margins, may be sheared. Migmatitic varieties include mafic schlieren and are locally banded.

Essential minerals of the porphyritic category are oligoclase, microcline, quartz, variable amounts of hornblende, and minor biotite (commonly altered to chlorite). Quartz and oligoclase are commonly intergrown to produce myrmekite. Accessory minerals include sphene, apatite, zircon, allanite and opaques; secondary minerals are sericite, chlorite, epidote, clinozoisite, calcite and prehnite. Hornblende is occasionally porphyroblastic and rimmed by biotite; it is also replaced by epidote. The groundmass of these rocks generally has a xenomorphic granular texture.

ALKALI-FELDSPAR GRANITE

Alkali-feldspar granite forms a very minor part of the Pilbara Block. The principal intrusions identified on Plate 1A are those near Strelly, Marble Bar, Yilgalong Creek and in the Gregory Range. The rock is normally medium- to coarse-grained and unfoliated, except in the Gregory Range. At Marble Bar it intrudes the Duffer Formation and contains some greenstone xenoliths; it is generally leucocratic and contains perthite, biotite and minor magnetite. The Strelley mass is granophyric, and the Yilgalong intrusion is rich in albite and quartz. Alkali-feldspar granite crops out 15 km east of Mount Sydney in the Gregory Range. The rock is medium- to coarse-grained, well foliated, and contains bands of martite granite (martite forming up to 50 per cent of such bands).

Perthite and quartz are the dominant constituents of the alkali-feldspar granites. Minor biotite may be present, and secondary minerals include sericite, sphene, chlorite, epidote, calcite, rutile and leucoxene. Zircon is unusually abundant, and magnetite is quite common.

POST-TECTONIC GRANITE AND ADAMELLITE

The most distinctive, and economically most important, granitic intrusions of the Pilbara Block are composed of poorly foliated, medium- to coarse-grained, equigranular biotite granite and adamellite. Eleven large plutons are shown on Plate 1A. Most intrude the older granitic complex but some are partly or completely bounded by greenstones. The post-tectonic nature of the plutons is established by the fact that they do not exhibit deformation effects associated with the main episode of doming. Biotite foliation and migmatitic banding in the older granitic complex are sharply truncated at contacts with these "younger" intrusions, several of which have been dated at 2 700 to 2 600 m.y. As noted by Blockley (1980), the post-tectonic granites are not only lithologically distinctive by also geochemically very different from other rocks of the batholiths. In particular K/Na, Rb/Sr and Rb/K ratios are exceptionally high. Such potassic, post-tectonic granitic plutons have previously been identified in several other Archaean shield areas of the world (e.g. Barberton Mountain Land of South Africa).

The post-tectonic granitic rocks crop out typically as rugged hills, exfoliated domal masses, and boulder fields, in contrast with the generally more subdued topography of sand plains covering the older complex. Topography is sufficiently distinct to permit plotting many of the intrusions from satellite (ERTS) photographs (Frontispiece). It should be noted however that topograph expression is not an infallible guide to the distribution of these rocks. Porphyritic granite also forms exfoliated domes, and residual inselbergs do form tors within the large expanses of migmatitic granite in the plains.

Although normally massive, the post-tectonic granites and adamellites locally possess a weak primary foliation and broad-scale compositional banding; both features probably originated during magmatic intrusion. The origin of the post-tectonic plutons is discussed by de Laeter and Blockley (1972), Hickman (1975b) and Blockley (1980) who conclude that they were emplaced as magmatic intrusions by a process of stoping rather than forceful injection. The magma is believed to have been derived by partial melting of pre-existing crust, probably the older complex. Crustal melting at depth could have occurred close to gathering pools of basaltic magma (later to be extruded as the Fortescue Group) (Blockley, 1980) or in the high temperature, low confining pressure environment beneath the major synclines which were produced by the main episode of deformation (Hickman, 1975b). Downward movement of the older complex during the deformation probably carried it close to the base of the crust. Initial $^{87}Sr/^{86}Sr$ ratios of the post-tectonic intrusions are generally 0.74 to 0.73, far greater than would be expected in material derived directly from the mantle.

Blockley (1980) considers that the post-tectonic plutons lie in linear belts; one belt trends west-northwesterly taking in the Bonney Downs, Mondana, Cooglegong and Numbana intrusions; a second trends northeasterly including the Coondina, Cooglegong and Moolyella Adamellites; and a possible third trends northwesterly, embracing the Cookes Creek Granite, the Moolyella Adamellite and several small intervening stocks. Hickman (1975b) pointed out that the post-tectonic plutons occur preferentially within synclines or at the margins of synclines along granite-greenstone contacts. The first of Blockley's belts is a fairly well defined feature, and plutons occur where the third belt intersects synclines, but the second trend is more tenuous. Blockley suggests that the belts were Late Archaean to Early Proterozoic zones of crustal weakness.

The post-tectonic granite and adamellite intrusions are economically important because of their associated tin deposits; in the past they were often referred to as the "tin granites". During emplacement the more volatile and crystallographically less compatible elements became concentrated towards the tops of the plutons, causing alteration of such minerals as biotite and plagioclase and finally forming residual fluids which crystallized as pegmatite veins near the intrusive contacts. Such pegmatites contain cassiterite, tantalite-columbite minerals, beryl, lepidolite, fluorite, barite and sparse gadolinite. Where the pegmatites invade greenstones minerals of Bi, Mo and Cu are locally encountered (e.g. Cookes Creek Granite).

Essential minerals of the post-tectonic plutons are quartz, microcline (commonly perthitic), plagioclase (oligoclase or albite) and variable amounts of biotite and muscovite; biotite is partly replaced by chlorite, and plagioclase by sericite or epidote. Accessory minerals include apatite, zircon, fluorite, magnetite, spessartine, sphene, allanite, clinozoisite, topaz, tourmaline and stilpnomelane. Where albite is present, as in the Moolyella Adamellite, it is commonly zoned and contains altered cores. Porphyritic phases contain euhedral microcline, commonly with carlsbad twins. Blockley (1980) notes large poikiloblastic microcline megacrysts in the Cooglegong Adamellite near Coomba Creek. Most rocks have a hypidiomorphic granular texture. Quartz occurs as large euhedral, often compound, grains and as smaller rounded inclusions in microcline; it may be strained, granulated or sutured and in some sections contains inclusions of apatite, epidote or even amphibole (Blockley, 1980). Microcline forms one-half to two-thirds of the feldspar present. It ranges from anhedral to euhedral, and is typically poikilitic, enclosing rounded grains of quartz and plagioclase.

BATHOLITHS AND OTHER PLUTONS

As can be seen on Plate 1A, the area's batholiths contain numerous individual plutons, and it seems certain that many more, as yet unrecognized, intrusions exist within the older complex. The batholiths are described in an order which essentially corresponds to how well they are known.

SHAW BATHOLITH

The Shaw Batholith (Figure 3) is a complex domal structure, occupying about 3 300 km^2, and elongated in a north-south direction. The western margin of the batholith is marked by a shear zone dipping steeply westwards; the northern contact is largely intrusive; the eastern boundary is a zone of moderate shear inclined eastwards; and the southern contact is an unconformity against the Fortescue Group. Foliation directions within the mass show that it contains several subsidiary domes and intervening synclinal belts. Examples of the latter run northwards and southeastwards from Coondina, and an east-west trending syncline appears to exist in the area occupied by the Cooglegong Adamellite.

Blockley (1980) states that the most primitive rock in the batholith is stromatic migmatite containing numerous inclusions of amphibolite. This rock is exposed 8 km west of Pilga where it was dated by de Laeter and others (1975) at 2 951 $\pm$ 83 m.y. Oversby (1976) dated rocks from the area at 2 936 $\pm$ 9 m.y. (Pb-Pb mineral isochron), but comments that this is a metamorphic age; the primary age is unknown, but not considered to be much greater*. Since the migmatite intrudes the adjacent Western Shaw Belt (greenstones), Blockley implies that the batholith contains no pre-greenstone granitic rocks. Mapping south of Hillside homestead however suggests that such material may exist close to large mafic xenoliths and xenolith trails. These xenoliths are not obviously related to the principal greenstone belts and might pre-date the Talga Talga Subgroup rocks. Future searches for evidence of the hypothetical sialic basement could be concentrated in such areas. Rb-Sr geochronology should avoid rocks close to batholith margins which are normally either intrusive or strongly deformed (i.e. probably "up-dated" by metamorphism).

Ancient rock may be preserved on the eastern flank of the batholith south of Split Rock where granitic rocks are structurally concordant with, and underlie, the Talga Talga Subgroup. Another area, which field evidence suggests might contain old material, is the structurally complex region northwest of Canning Tin; here a system of domes and synclines deforms both the layered succession and the concordantly underlying granitic rocks. Cores of granite domes are relatively undeformed.

Seven plutons shown on Figure 3 were originally named and briefly defined by Hickman and Lipple (1975). The following descriptions are partly based on unpublished work by Lipple who compiled information obtained by himself, Blockley and Hickman.

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*Pidgeon (1978b) has recently dated migmatite from the batholith at 3 417 $\pm$ 40 m.y. using the U-Pb method on zircon.

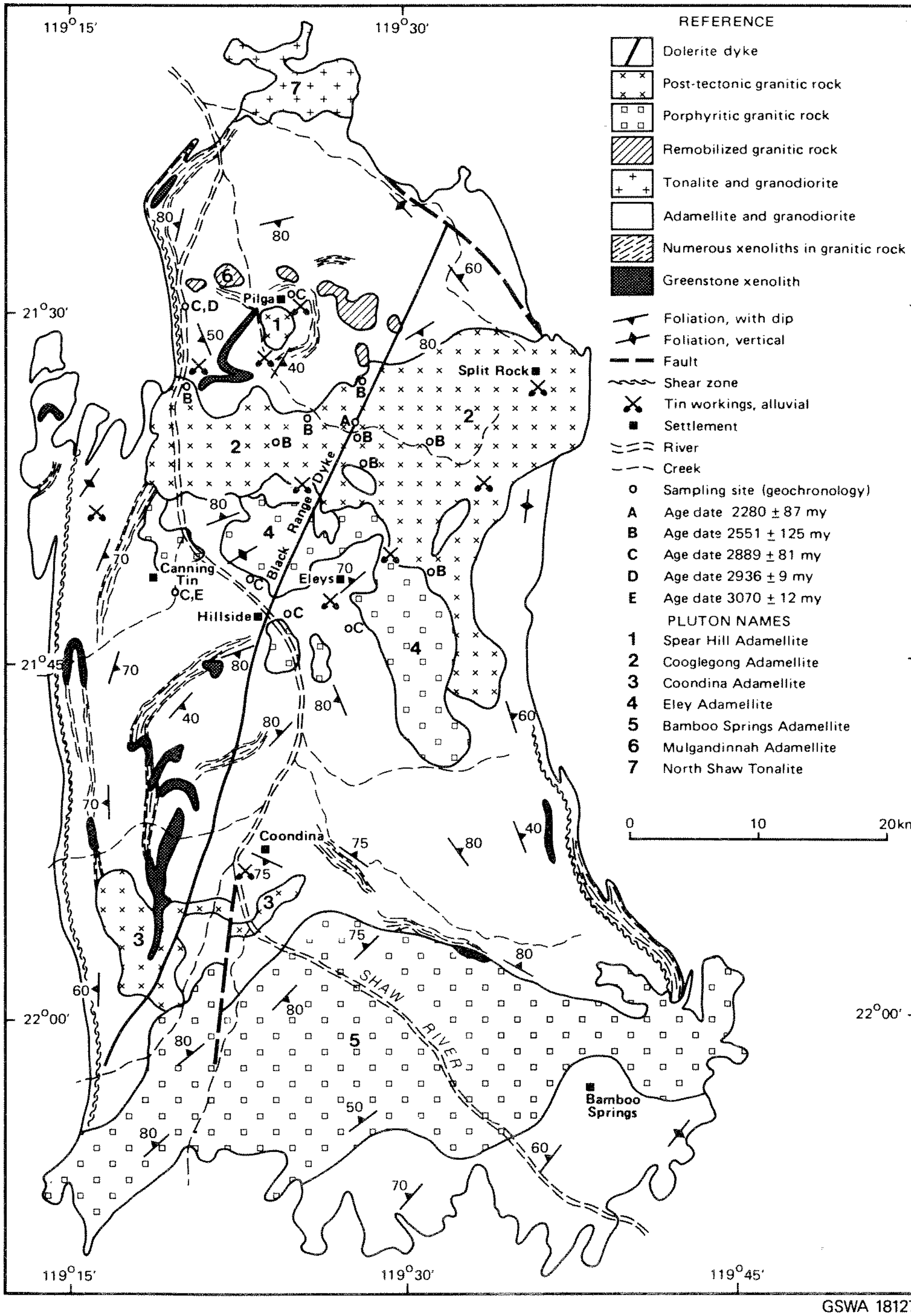


Figure 3. Geology of the Shaw Batholith.

Spear Hill Adamellite

The Spear Hill Adamellite is restricted to the type locality, Spear Hill, where it crops out extremely well over an area of 8 km^2. The rock is a massive, coarse, even-grained biotite adamellite containing porphyritic or coarse granophyric areas. Microcline exceeds calcic oligoclase (average composition An_{28} for seven samples) and is characterized by coarse, twinned exsolution blebs of oligoclase. Large masses of perthitic microcline also enclose pre-existing crystals of oligoclase.

The boundaries between the post-tectonic Spear Hill Adamellite and the surrounding granitic complex are sharp and easily mapped. Along its northwestern margin, the adamellite intrudes a large xenolith of Archaean amphibolite and quartzite in migmatite. The pluton is itself intruded by Archaean rhyolite dykes and Lower Proterozoic dolerite dykes. The intrusion is thus Archaean and probably represents an off-shoot of the Cooglegong Adamellite, which it resembles in appearance and composition.

Cooglegong Adamellite

The Cooglegong Adamellite derives its name from Cooglegong Creek, which drains a large part of its outcrop. The total area of the pluton is 360 km^2 in which the principal rock type is a medium- to coarse-grained, poorly foliated biotite adamellite with microcline predominant over plagioclase. Broad-scale banding due to variations in phenocryst content is present near Split Rock. The type locality of the Cooglegong Adamellite is Cooglegong Creek, about 10 km southeast from Spear Hill, where the rock is even grained with a hypidiomorphic granular texture.

Microcline is usually microperthitic; and in porphyritic zones (most widespread on the eastern side of the intrusion), large microcline phenocrysts are commonly mantled by plagioclase, and poikilitically enclose plagioclase and quartz. Plagioclase has an average composition of calcic oligoclase ranging from oligoclase (An_{26}) to sodic andesine (An_{31}). Myrmekite occurs in small amounts, but locally forms a significant component of the rock. The northern margin of the pluton is locally granophyric.

The rock is well jointed, generally massive and poorly foliated. Near the Black Range Dyke, a strong foliation due to shear is exhibited by feldspar, mica and quartz. Xenoliths of the surrounding medium-grained foliated or migmatitic granodiorite are distributed through the pluton but are most common near its northern margin and near Eleys. The topographic expression of the pluton is similar to that of the Spear Hill Adamellite, rocky hills and tors being typical.

The boundary between the Cooglegong Adamellite and surrounding granitic rocks of the older complex is generally clear cut, and shows up quite well on air photographs. On its southwestern side, the intrusion is bounded by the Eley Ademellite, which generally crops out as scattered inselbergs. Like the Spear Hill Adamellite, the Cooglegong Adamellite is intruded by Archaean rhyolite and dacite dykes and by Lower Proterozoic dolerite dykes. Geochronology by de Laeter and others (1975) yielded an age of 2 606 $\pm$ 128 m.y. (recalculated to 2 551 $\pm$ 125 m.y.) with an initial $^{87}Sr/^{86}Sr$ ratio of 0.7303 $\pm$0.028.

Coondina Adamellite

The Coondina Adamillite crops out over an area of 50 km^2 southwest of Coondina (Figure 3). The intrusion is named after Coondina Pool on the Shaw River. Good exposures of the intrusion are available 3 km south of Coondina. It is predominantly medium to coarse, equigranular, massive biotite adamellite containing subequal microcline and calcic oligoclase. Plagioclase is normally sericitized and some perthite is partly replaced by muscovite fans.

The eastern part of the intrusion crops out as well-jointed, low, rocky ridges, but the western portion is partly obscured by colluvial sand. Intrusive contacts are well defined, largely because of contrasting topographic expression with the plains over the older complex. Cassiterite mined from superficial deposits at Coondina is thought to have been derived from pegmatites associated with the intrusion.

Eley Adamellite

The Eley Adamellite, which derives its name from the Eley mining centre, crops out over an area of about 120 km^2. Parts of the pluton are well exposed, but much of it is represented by scattered, rounded tors and humpback hills. The rock is a medium- to coarse-grained porphyritic biotite adamellite. A moderate to prominent foliation is formed by mafic schlieren and an alignment of feldspar phenocrysts, biotite and quartz grains in the groundmass. There are abundant xenoliths of medium-grained biotite granodiorite and less common amphibolite. Microcline phenocrysts range up to 30 mm in length and are typically twinned with inclusions of quartz, plagioclase and biotite. The phenocrysts are set in an allotriomorphic granular groundmass of fresh sodic oligoclase, myrmekite, microcline, quartz, biotite and subordinate sphene. Oligoclase exceeds microcline, and near the western margin of the intrusion oligoclase phenocrysts are set in a groundmass of microcline and oligoclase.

The southwestern margin of the Eley Adamellite is transitional; adjacent migmatite is intruded by veins of porphyritic adamellite, which taper away from the contact. As noted above, the contact between the Eley Adamellite and the Cooglegong Adamellite is sharp. Smaller porphyritic medium- to coarse-grained biotite adamellite plutons southwest and west of the Eley Adamellite are probably cogenetic, and some may be connected to it at depth.

Bamboo Springs Adamellite

The Bamboo Springs Adamellite crops out over 600 km^2 of country northwest of Bamboo Springs homestead. Exposure is generally rather poor, but exfoliated domes, tors and rock platforms provide excellent opportunities to study the rock (e.g. along with the type section on the road linking Bamboo Springs with Hillside).

The Bamboo Springs Adamellite is composed of medium- to coarse-grained porphyritic biotite adamellite. A prominent, steeply inclined foliation is exhibited by banding, biotite schlieren, and an alignment of feldspar phenocrysts, biotite and grains of quartz. This foliation generally strikes northeast, but in the northeastern part of the pluton it is parallel to the contact. The pluton has a well-defined contact on its northeastern side, but elsewhere poor exposure and limited field investigations make the limits less definite. Xenoliths of the older granitic complex are common near the northern contact and the intrusion sends apophyses into the country rock.

In thin section the rock consists of microcline phenocrysts set in a allotriomorphic granular groundmass of oligoclase, microcline, quartz and biotite. Some of the microcline phenocrysts measure up to 20 mm in length, and others have ragged outlines. Quartz is locally concentrated into large patches surrounded by biotite.

Mulgandinnah Adamellite

The Mulgandinnah Adamellite derives its name from the type locality, Mulgandinnah Hill. The rock crops out as a series of irregular-shaped stocks east and west of Pilga. The largest individual mass occurs 5 km east of Pilga, but the size of this has been exaggerated on the map. The name "Mulgandinnah Adamellite" should strictly apply only to the intrusion at Mulgandinnah Hill since there is no evidence to suggest that the various outcrops represent cupolas of a single mass.

The intrusions represent megascopic neosome segregations within a zone of agmatite. All such bodies might loosely be referred to as Mulgandinnah Adamellite. The rock is a fine- to medium-grained, equigranular and well-foliated biotite adamellite; the foliation takes the form of aligned biotite schlieren and wisps, feldspars, mica and elongate xenoliths of migmatitic palaeosome. Essential minerals are microcline, saussuritized plagioclase (generally calcic oligoclase) and subordinate biotite. The rock is typically allotriomorphic granular, but a foliation may be outlined by elongate quartz blebs, and protoclastic shear is not uncommon. The contacts of the Mulgandinnah Adamellite are normally diffuse and ill defined, and apophyses of the various stocks intrude foliation planes within the surrounding older complex. However, sharp cross-cutting contacts with the migmatite have been observed (Blockley, 1980 Fig. 15E).

North Shaw Tonalite

The North Shaw Tonalite crops out over 35 km^2 at the northern end of the Shaw Batholith around North Shaw Well, which is the type locality. The intrusion is an equigranular, poorly foliated biotite tonalite.

Near North Shaw Well the rock is a pink to grey, fine-grained biotite tonalite with euhedral sericitized oligoclase, quartz, chlorite (after biotite) opaque iron oxide and minor microcline. Other variations of the pluton south and east of North Shaw Well are medium- to coarse-grained biotite granodiorite, and medium-grained hornblende biotite granodiorite containing hornblende phenocrysts. Igneous textures are generally well preserved, suggesting that the North Shaw Tonalite is probably younger than the migmatitic complex to the south.

YULE BATHOLITH

Figure 4 shows the principal subdivisions of the Yule Batholith which, with an area of approximately 6 000 km^2, is one of the larger batholiths in the craton. At its southern and western margins, the structure is unconformably overlain by Proterozoic rocks of the Fortescue Group, whereas its northern and eastern contacts are either tectonic or intrusive. At three points the boundary of the batholith is arbitrarily drawn across narrow tracts of granitic rocks; two of these occur in the north, 7 km and 15 km east of Wodgina, and the third lies in the extreme southeast (Plate 1B).

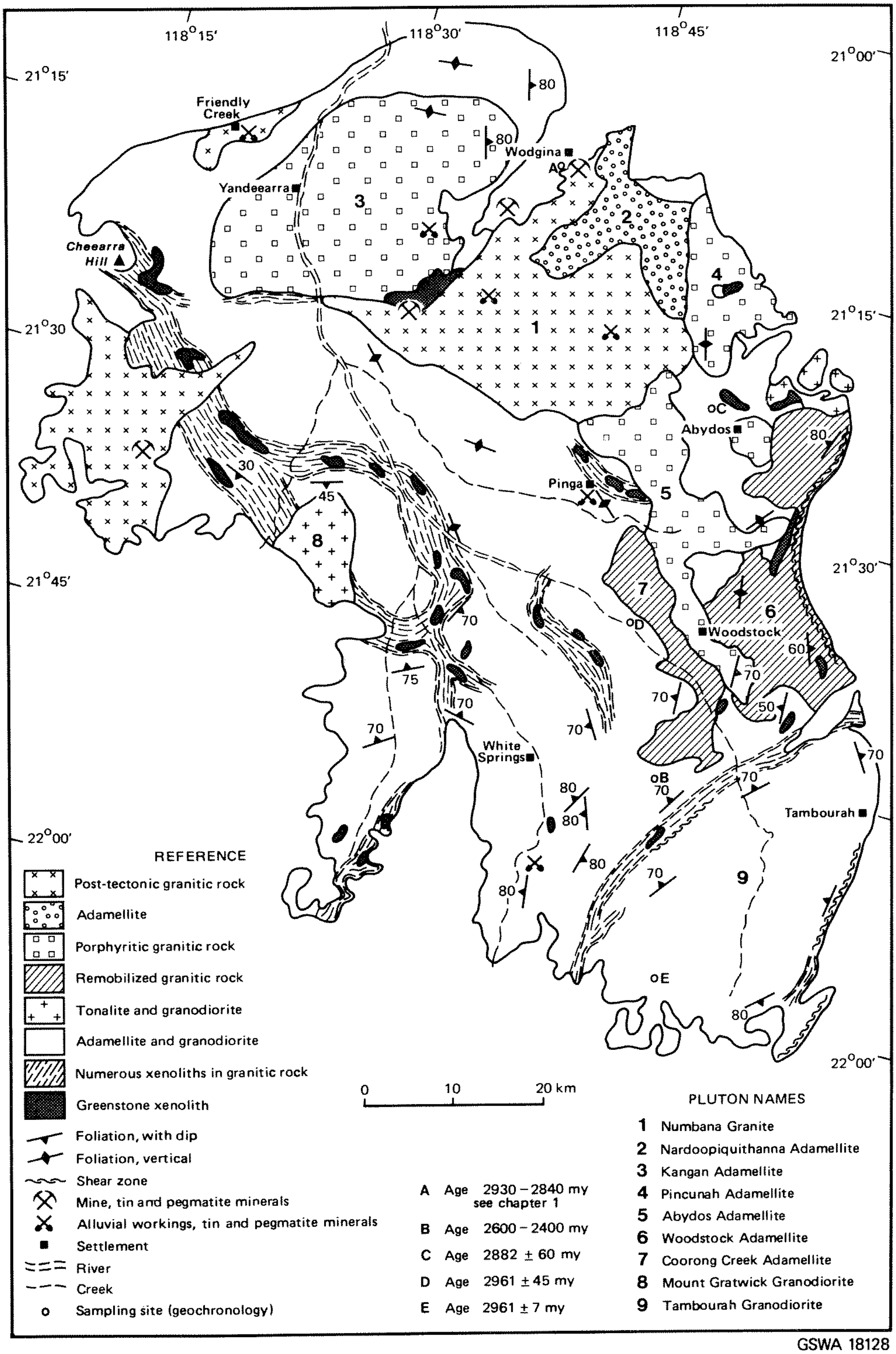


Figure 4. Geology of the Yule Batholith.

As in the Shaw Batholith, internal structure is complex, and has not been fully resolved. Several trails of greenstone xenoliths (Fig. 4) within migmatitic zones may represent synclinal belts formed prior to the main episode of dome and syncline development; however they might equally well be interpreted as root zones of D2 synclines. One such D2 root zone is preserved on the northeastern side of the Tambourah Granodiorite. Foliation patterns within the batholith indicate several dome and syncline structures.

Two unnamed post-tectonic plutons are mapped, one at Friendly Creek and one south of Cheearra Hill. Recognition of the latter is based on company reports, photo interpretation and mineral composition. Pegmatite veins associated with albite adamellite at Mumbeillina have been mined for beryl. The host rock contains 40 per cent albite, 30 per cent quartz and 25 per cent microcline in a fine, even-grained groundmass. A second intrusion at Friendly Creek contains pegmatite dykes that have shed considerable amounts of cassiterite. The rock is a medium-grained albite adamellite and chemical analysis has revealed high Rb/Sr and K_2O/Na_2O ratios.

Numbana Granite

The Numbana Granite, which derives its name from Numbana mine, crops out over an area of 500 km^2. Following detailed work by Blockley (1980), porphyritic granite south of Wodgina (Plate 1A) is included in the intrusion. The pluton is a medium to coarse, even-grained, poorly to moderately foliated granite with abundant finer grained granitic xenoliths and rare mafic schlieren. Near its contact with the Pilbara Supergroup at Wodgina, the Numbana Granite grades into marginal leucocratic phases which are either foliated or pegmatitic. Prominent pegmatite veins, in most places closely associated with the marginal granite, intrude the greenstones and provide a source of tin, tantalum and beryllium minerals. Across most of its outcrop the Numbana Granite is exposed in low rocky hills and tors separated by short expanses of alluvial sand. Jointing and quartz veining along shear zones and faults are common features of the mass.

In thin section, the rock has a typical granitoid texture with microcline (partly perthitic), albite, quartz and biotite (partly replaced by chlorite). The leucocratic marginal phase on the pluton's western side contains spessartine, zircon and allanite.

The Numbana Granite possesses a transitional northern contact with the older Nardoopiquithanna Adamellite, xenoliths of which are common near the margin. On its southern side the pluton intrudes the older complex.

The age of the Numbana Granite is considered to be similar to that of the Moolyella Adamellite (2 614 m.y.) which it closely resembles. Dates obtained by Greenhalgh and Jeffery (1959) on pegmatite minerals from Wodgina are older than would be expected if the pegmatite vein were emanations from the Numbana Granite (given the above analogy). It is probable, however, that the pegmatites at Wodgina may be related to the older complex; as noted by Blockley (1980), tin and tantalum mineralization, such as that associated with the Wodgina rocks, is not confined to post-tectonic intrusions.

Nardoopiquithanna Adamellite

The Nardoopiquithanna Adamellite, which derives its name from Nardoopiquithanna Pool, occupies an area of approximately 125 km². Sections through the intrusion, which crops out across relatively inaccessible terrain, are available on a track leading northwestwards from the Port Hedland to Wittenoom road near Kunagunarrina Pool. The intrusion is composed of massive to poorly foliated, fine- to medium-grained biotite adamellite. The rock is strongly jointed, a feature reflected in its rugged scenery. No petrographic work has been carried out on the pluton.

The topographic expression, lithology and photopattern of the Nardoopiquithanna Adamellite are similar to those of the Numbana Granite, and the two might have been regarded as parts of a single intrusion, were it not for the fact that the Numbana Granite contains xenoliths of the Nardoopiquithanna Adamellite. The northern contact of the pluton is more distinct; massive fine-grained adamellite abuts against well-foliated, migmatitic granodiorite of the older complex. The age of the intrusion is probably similar to that of the Numbana Granite.

Kangan Adamellite

The Kangan Adamellite crops out over an area of 180 km² between Kangan homestead and Mount Francisco. Exposure is generally poor, but large outcrops are accessible a short distance to the northwest of Mount Francisco. The pluton is chiefly biotite adamellite to granite, and is porphyritic throughout, euhedral microcline phenocrysts up to 20 cm long being set in a medium- to coarse-grained groundmass. Phenocrysts are well twinned, contain numerous inclusions of plagioclase, and in some cases are rimmed by albite. Plagioclase, ranging in composition from oligoclase to sodic andesine, is locally corroded by quartz and generally partly sericitized. Minor amounts of muscovite are present, as are accessory hornblende sphene, magnetite and, rarely allanite.

The Kangan Adamellite occupies the centre of a dome flanked by greenstones and migmatite rich in greenstone xenoliths (Fig. 4). To the north, east, and west, it intrudes migmatitic granodiorite, and at Mount Francisco, it is bounded by greenstones and the Numbana Granite. Although the contact between the Numbana Granite and the Kangan Adamellite is well defined, intrusive relations have not been established. It is assumed however that, since the porphyritic adamellite is normally well foliated and the granite is massive, the Numbana Granite is younger.

Pincunah Adamellite

The Pincunah Adamellite crops out over an area of 165 km² near Pincunah waterhole after which the pluton is named. Good exposures of the intrusion exist in the Turner River and along the Port Hedland to Mount Newman Railway. The rock is a medium- to coarse-grained porphyritic biotite adamellite. A strong foliation is exhibited by alignment of microcline phenocrysts (up to 20 mm long), biotite, and mafic schlieren. Amphibolite, ultramafic schist and granodiorite xenoliths are locally abundant, and the rock is commonly stromatic.

Microcline phenocrysts are well twinned, and contain albite-rimmed plagioclase inclusions. The groundmass of oligoclase, microcline, quartz and biotite possesses an allotriomorphic texture. Much of the partly recrystallized plagioclase is small myrmekitic grains between larger grains. Plagioclase is in excess of microcline, but the pluton varies in composition to biotite granodiorite and tonalite, probably due to partial assimilation of greenstone material.

The eastern part of the Pincunah Adamellite intrudes greenstones of the Pilgangoora Belt, and the pluton post-dates migmatitic granodiorite to the north and south; its relationship to the Nardoopiquithanna Adamellite and Numbana Granite have not been directly observed, but it is probably older.

Abydos Adamellite

The Abydos Adamellite is an irregular elongate mass of medium- to coarse-grained porphyritic biotite adamellite cropping out over 160 km^2 southwest of Abydos homestead. Accessible exposures of the pluton are available on the Mount Newman Railway and west of Abydos landing ground. The rock is well foliated by an alignment of biotite schlieren, microcline phenocrysts (up to 30 mm long) and quartz. Microcline phenocrysts contain biotite, quartz and albite-rimmed plagioclase inclusions, much like the Pincunah Adamellite. The groundmass is allotriomorphic granular, and is composed of oligoclase, microcline, quartz and subordinate biotite and hornblende. Oligoclase and plagioclase occur in approximately equal amounts.

The Abydos Adamellite intrudes the older migmatitic complex. Contacts are transitional and the marginal zone is only slightly porphyritic. On its northwestern side, the intrusion abuts against the Numbana Granite, but age relations are uncertain.

Woodstock Adamellite

The Woodstock Adamellite crops out over an area of 260 km^2 east and northeast of Woodstock homestead. The pluton is well exposed northeast of Mundine Well, around Dead Bullock Well and in the upper reaches of Coorong Creek and the Turner River. The rock is similar to that forming the Pincunah Adamellite, but microcline phenocrysts are only conspicuous in the northern part of the intrusion. A primary foliation formed by feldspar, mica, quartz and biotite is over-printed or destroyed by a tectonic foliation consisting of quartz, mica and feldspar alignment. Plagioclase is generally sericitized, and biotite is variably chloritized.

The Woodstock Adamellite has transitional margins with the migmatitic complex, and xenoliths of the latter are common. This feature indicates that the intrusion originated by remobilization of the older granitic rocks (cf. Mulgandinnah Adamellite). The Woodstock Adamellite intrudes the Abydos Adamellite and greenstones of the Soanesville Syncline, but its northeastern margin is a fault.

Coorong Creek Adamellite

The Coorong Creek Adamellite, which crops out over approximately 110 km^2 around the lower reaches of Coorong Creek, is a medium to coarse even-grained biotite adamellite. Good exposures exist west of Woodstock homestead above the confluence of the creek with the Yule River. Phenocrysts are rare, and the rock is poorly or moderately foliated by an alignment of feldspar, biotite, quartz, biotite wisps, and mafic schlieren. This foliation is best developed in the northern part of the mass, which also contains amphibolite and granodiorite xenoliths. Main rock-forming minerals are microcline, oligoclase, myrmekite and quartz. Biotite is a minor constituent, and accessories include apatite, zircon, sphene and opaques.

Like the Woodstock Adamellites the Coorong Creek intrusion probably originated by remobilization of the older complex. Contacts with the latter are transitional.

Mount Gratwick Granodiorite

The Mount Gratwick Granodiorite, which crops out in isolated low exposures north of Mount Gratwick, is a poorly foliated, medium-grained granodiorite. Its total area is difficult to ascertain, but appears to be about 100 km^2. Exposures are available along the Yandeearra road which leaves the Port Hedland to Wittenoom road 2 km north of White Springs homestead. The rock is cream coloured, leucocratic, and resembles anorthosite. Although poorly foliated it contains some biotite schlieren and amphibolite xenoliths, but it consists principally of calcic oligoclase, subordinate quartz, accessory microcline, opaques and apatite; chlorite, epidote and sericite are secondary minerals. According to mineral proportions the rock has a composition close to that of leuco-diorite.

The granodiorite is part of the older complex; its foliation patterns (striking east-west) conform to those of the surrounding migmatitic granitic rocks. At its southern contact the pluton is unconformably overlain by Proterozoic rocks. The age of the rock is probably similar to that of the migmatitic rocks surrounding it but its composition might be interpreted as evidence of a greater antiquity.

Tambourah Granodiorite

The Tambourah Granodiorite crops out over 660 km^2 of chiefly rugged, inaccessible country around and to the south of the abandoned Tambourah homestead. Because large parts of the mass are inaccessbile to vehicles, the precise nature of its interior remains uncertain. The boundaries of the granodiorite are clearly defined by greenstones to the north and east, a xenolith-rich migmatite belt to the west and unconformable Proterozoic cover to the south. Migmatitic, nebulitic, gneissose and schistose varieties of the mass are readily observed along the Hillside to Woodstock road and good exposures are also available along the Port Hedland to Mount Newman Railway.

The rock is a well-foliated, nebulitic to stromatic, medium- to coarse-grained biotite granodiorite. Alignment of biotite, feldspar, quartz grains, leucosome veins, mafic schlieren and bands define the foliation. The pluton's margins are sheared, and contain numerous rafts of greenstone material. Although the dominant composition is biotite granodiorite, the northern part is chiefly biotite adamellite. In the southwest, the rock contains calcic oligoclase, quartz, microcline, biotite and locally hornblende with accessory apatite, zircon, allanite and opaques. Twinned perthitic microcline poikilitically encloses albite-rimmed plagioclase in some sections. The composition of the northern part of the mass is similar, except that microcline is more abundant and ilmenite, sphene and fluorite are accessories. Small veins of pumpellyite and ankerite are noted at some localities. Secondary minerals are similar to those in other plutons.

The name "Tambourah Granite" was used without definition for the same mass by Noldart and Wyatt (1962). Oversby (1976), using granodiorite collected at the 127 Mile Quarry on the Mount Newman Railway, established that the pluton was metamorphosed at 2 961 ± 7 m.y.

MOUNT EDGAR BATHOLITH

The geology of the Mount Edgar Batholith is outlined in Figure 5. The southwest and southeast boundaries of the batholith are essentially tectonic, whereas the northwest and northeast contacts are intrusive. Near Coppin Gap and Bamboo Creek, biotite adamellite forms stocks, which have penetrated about 10 km into the layered succession. The rock contains a tectonic foliation broadly parallel to the batholith margin, and consequently must have formed either during or prior to the doming process. J. R. de Laeter (pers. comm.) has dated samples of granodiorite and porphyry collected by Esso Australia Ltd from one such intrusion at Coppin Gap. Initial results indicate an age of 2 915 ± 207 m.y. (R_i 0.706 7 ± 0.003 9), but the work has yet to be completed.

Most of the batholith is composed of foliated biotite granodiorite and adamellite, but 15 km east of Marble Bar there is a post-tectonic pluton, the Moolyella Adamellite. Almost one-quarter of Western Australia's total production of tin concentrate has been obtained from alluvium derived from pegmatites which fringe this intrusion. About 15 km north of Moolyella, tin has been obtained from a poorly foliated albite adamellite that intrudes the northern contact of the batholith. The boundaries of this pluton are drawn from photo interpretation; a chemical analysis of the rock is presented in Appendix C. Photo interpretation also suggests the existence of smaller post-tectonic plutons in the centre, and at the eastern contact of the batholith. Post-tectonic bodies east-southeast of Mount Edgar homestead appear to be unmineralized.

Blockley (1980) identifies a discrete intrusion of foliated biotite granodiorite 2 km northeast of Moolyella. The pluton is considered to be of similar age to the rest of the older complex in this batholith (3 300-2 900 m.y.) but must be slightly younger because it contains xenoliths of migmatite. Irregular bodies of granodiorite that intrude the contact between the batholith and the Talga Talga Subgroup northwest of Moolyella are probably syntectonic intrusions formed during the main episode of doming. Approximately 35 km east-northeast of Mount Edgar homestead fieldwork has established the existence of a muscovite-rich granitic body. It is unclear whether this is a separate intrusion or merely a greisenized part of the older complex.

An interesting component of the Mount Edgar Batholith is a pluton of alkali feldspar granite immediately east of Marble Bar. Hickman and Lipple (1975) suggest that this granite may represent a local magmatic source for the Duffer Formation. Xenoliths of the granite occur within the migmatitic complex near its eastern contact (Lipple, pers. comm.) indicating that it forms an ancient part of the batholith. The rock crops out over 10 km^2 of hilly country east and south of Marble Bar; it has no clear foliation, but does contain some greenstone xenoliths. Its principal mineral components are perthite and quartz with subordinate magnetite and biotite and common zircon and sphene. Secondary minerals are chlorite, biotite and fluorite.

Four of the twelve granitic samples used by Compston and Arriens (1968) to estimate the age of Pilbara granites at 3 050 m.y. were collected from the older complex in the southern part of the batholith. These have since been recalculated (de Laeter pers.

comm.) to be 3 279 ± 169 m.y. old. Pidgeon (1978b) dated zircons from granitic rocks of the older complex near Moolyella at 3280 ± 20 m.y.

Moolyella Adamellite

The Moolyella Adamellite was first recognized by Blockley (1970) and named the "Moolyella Granite" by de Laeter and Blockley (1972). The pluton crops out over 55 km² of rugged terrain to the east of Moolyella mining centre (Fig. 5). Excellent exposures of the pluton are available 1 km southeast of the mine camp, where rock platforms show abrupt contacts with the migmatic complex. The rock is a medium-grained, poorly foliated albite adamellite with an allotriomorphic granular texture.

Microcline and albite are generally present in approximately equal proportions although plagioclase content increases towards the western margin of the intrusion. Quartz is the other main constituent and occurs as large anhedral, often compound, grains and as small rounded inclusions in microcline. Biotite, partly altered to chlorite, makes up from 3 to 6 per cent of the adamellite, and occurs in clusters or as isolated flakes. Albite is variably altered to sericite, epidote and carbonate minerals, but microcline is generally fresh, polysynthetically twinned, and microperthitic with fine spindle-shaped plagioclase inclusions. Accessory minerals include epidote, fluorite, spessartine, and topaz; secondary muscovite replaces biotite.

Blockley (1980) describes three, late-stage phases of the intrusion, namely aplite, greisen and pegmatite. The aplite intrudes joints to form dykes composed of granular albite, quartz and green mica. Greisen, which occurs as small pipes within the pluton and as lenses near its margin, is composed essentially of quartz and muscovite with minor fluorite, magnetite and zircon. This type of rock appears to have originated principally by pneumatolysis although some is a product of cataclasis. Veins of layered aplite-pegmatite are concentrated on the western and southern sides of the Moolyella Adamellite. Most strike northerly through the migmatite complex, and are locally so numerous that they make up 20 per cent of the outcrop. The principal constituent minerals are quartz, albite, microcline, biotite, and accessory spessartine, green muscovite, cassiterite, beryl, zinnwaldite, lepidolite, fluorite, tantalite and magnetite.

The irregular shape of the pluton is interpreted as indicating that the present exposure level is close to its roof, and that this roof possesses major cupolas. Contacts with the migmatitic complex are steeply inclined and the distribution of pegmatite veins suggests that the pluton plunges westwards or southwestwards.

De Laeter and Blockley (1972) dated the Moolyella Adamellite at 2 670 ± 95 m.y. (recalculated to 2614 ± 93 m.y.) with an initial $^{87}Sr/^{86}Sr$ ratio of 0.7397 ± 0.0419, and concluded that the intrusion originated by partial melting of the older complex.

CORUNNA DOWNS BATHOLITH

The Corunna Downs Batholith is a relatively simple igneous structure (Fig. 5). The northern half of the batholith is composed chiefly of foliated granodiorite and adamellite containing several belts of greenstone xenoliths. To the south this unit is intruded by a crescent-shaped mass of porphyritic biotite and hornblende-biotite adamellite. Farther south the porphyritic adamellite is intruded by a similar crescent-shaped post-tectonic granitic pluton. The porphyritic rock contains the same tectonic foliations as the older complex, but the post-tectonic mass is largely unfoliated; both bodies were intruded along granite-greenstone contacts. Immediately west of Corunna

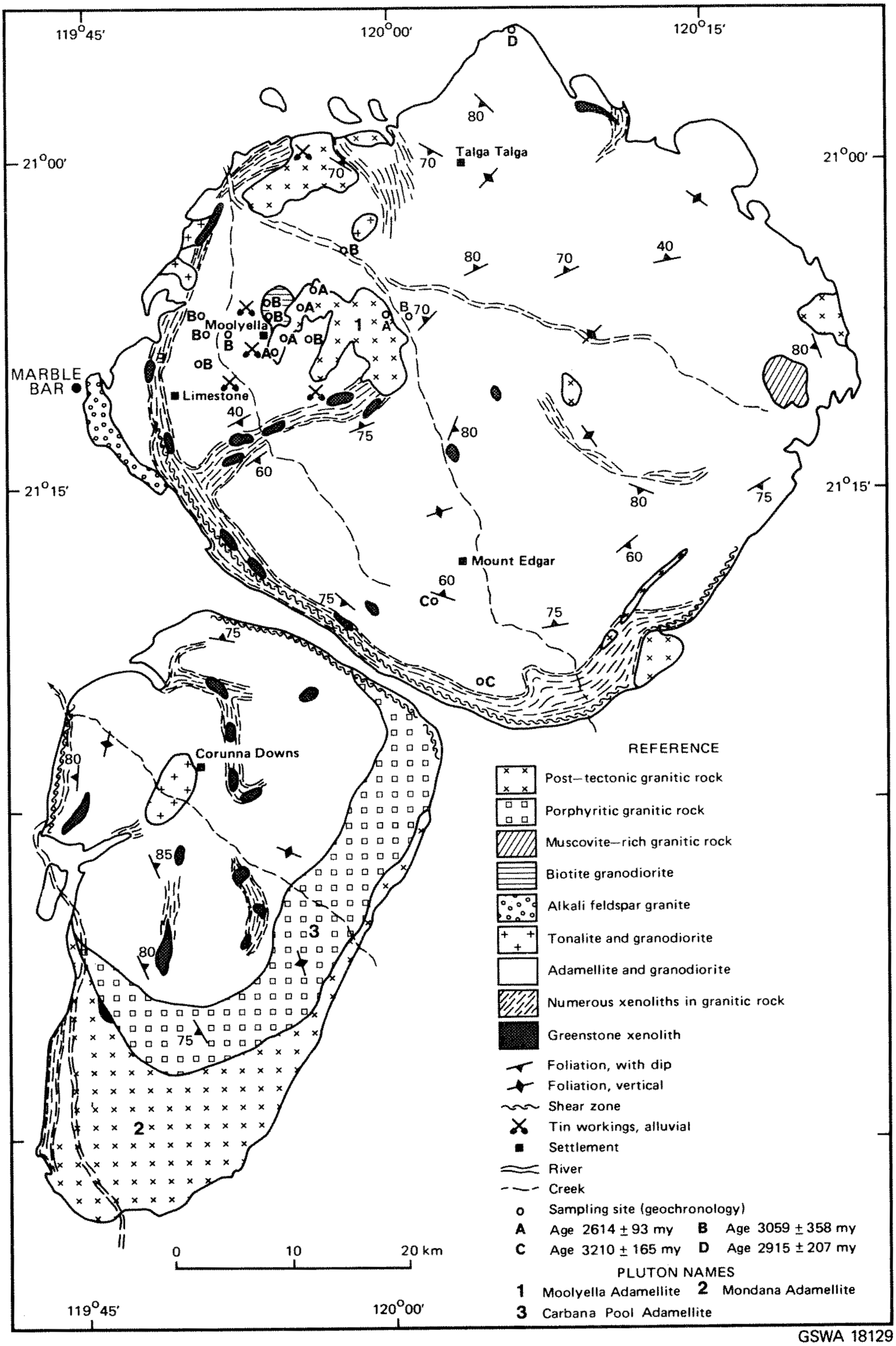


Figure 5. Geology of the Mount Edgar and Corunna Downs Batholiths.

Downs homestead is a poorly exposed mass of biotite tonalite. The rock is coarse grained, weakly foliated (biotite) and is composed of oligoclase, quartz, minor microcline and accessory sphene, apatite and opaque minerals. Secondary minerals are chlorite, epidote and calcite. Geochemical analysis reveals an unusually high mafic component, low silica content and a low Rb/Sr ratio. The rock may be a relatively ancient part of the older complex.

Outcrop across the Corunna Downs Batholith is poor, except in the southeast. The structural significance of the greenstone trails indicated on Figure 5 is consequently uncertain, but they appear to bear no relation to the geometry of surrounding greenstone belts. For this reason it seems probable that they originated prior to the main episode of doming, either by stoping from the Talga Talga Subgroup or by interfolding of greenstone and granitic material in a pre-Talga Talga Subgroup basement.

Mondana Adamellite

In 1972 systematic mapping by the Geological Survey confirmed the existence of a previously postulated (Blockley, 1970) post-tectonic intrusion in the southern section of the Corunna Downs Batholith. The pluton crops out over an area of 280 km^2 around Mondana Pool. Good exposures at Mondana Pool constitute a type area. The rock is a medium- to coarse-grained, poorly foliated to non-foliated biotite adamellite and biotite-hornblende adamellite. Texture varies from allotrimorphic granular to hypidiomorphic granular, and in some areas rare feldspar phenocrysts are present. Grain size diminishes slightly towards the margins of the pluton, where medium-grained aplite dykes are concentrated.

Microcline (usually perthitic) is in excess of oligoclase, the latter occuring as subhedral to euhedral grains up to 4 mm across. Oligoclase is twinned, zoned and variably sericitized. Other principal minerals are quartz, biotite (partly chloritized) and hornblende. Prehnite is a rather unusual secondary mineral.

The Mondana Adamellite has sharp intrusive contacts against Archaean greenstones along its southern margin and against the older Carbana Pool Adamellite to the north. The pluton also intrudes the Boobina Porphyry at Copper Hills. Geochemical analyses of the rock show it to be similar to other post-tectonic intrusions in the Pilbara Block (see Appendix C).

Carbana Pool Adamellite

Approximately 200 km^2 in area the Carbana Pool Adamellite derives its name from Carbana Pool which is the type locality. The rock is a foliated, medium- to coarse-grained porphyritic biotite adamellite with local hornblende biotite adamellite. Microcline phenocrysts with simple or polysynthetic twinning contain inclusions of quartz, biotite and albite-rimmed plagioclase. Subordinate, generally poorly twinned albite phenocrysts in the northeastern part of the pluton appear to replace microcline, suggesting soda-metasomatism. The groundmass is an allotriomorphic assemblage of microcline, oligoclase, quartz and minor biotite and hornblende. Intrusive relationships with the older complex to the north and the Mondana Adamellite to the south and east are described above. As is the case with most other porphyritic granitic intrusions of the block, geochemical evidence supports field observations that the composition of the rock is intermediate between that of the older complex and the post-tectonic granites.

The Carlindi Batholith is a large, poorly exposed structure occupying the northern part of the Pilbara Block between Port Hedland, the Gorge Range and Wodgina. Its boundaries with the Muccan Batholith and the Portree Granite are inferred on geophysical evidence and information obtained from drilling. The northwestern margin of the unit is concealed beneath coastal deposits. Exposures are virtually non-existent south of the Ord Range, between Tabba Tabba Creek and the Shaw River. Indeed, in the absence of drilling, there remains a possiblity that the narrow belt of greenstones at Strelley mine extends northeastwards (beneath superficial deposits) to connect with Archaean sedimentary rocks in the Ord Range. At present this is assumed not to be the case, and granitic rocks east and west of Tabba Tabba Creek are regarded as forming a single mass.

The batholith contains foliated granodiorite and adamellite, migmatite, porphyritic granitic rocks, and poorly foliated adamellite and granite of probable post-tectonic generation. Geochronolgy (Oversby, 1976) has been confined to the older complex and the porphyritic adamellite. The latter was studied at the 40 Mile Quarry on the Mount Newman Railway where the rock is exceptionally well exposed. Oversby could not determine the primary age of the adamellite, but recognized a metamorphic event at 2 245 ± 36 m.y.

At the 13 Mile Quarry the older complex has undergone obvious metasomatism. Numerous pegmatite veins intrude the rock, and garnet, muscovite and tourmaline are abundant. The primary age of the rock at this locality was estimated to be 2 920 m.y., subsequent metamorphic events occurring at 2 751 ± 31 m.y. and 2 085 ± 24 m.y. Pegmatites containing tin and tantalum have been worked at the Tabba Tabba and Strelley mines. Tabba Tabba is situated between two large post-tectonic plutons. Mineralization at Strelley appears to be related to the older complex, although here also the pegmatite ore bodies might have originated as late-stage emanations from a post-tectonic intrusion concealed beneath the greenstone syncline. There is no evidence that such an intrusion exists, however, and no geochronological work has been undertaken.

About 15 km to the northeast of Strelley homestead, granodiorite, diorite and tonalite occupy a few scattered small outcrops in poorly exposed terrain. The relationship of these rocks to the main body of adamellite and granodiorite to the south is uncertain. The rock is well foliated, migmatitic, stromatic and gneissic. Chemical analysis (Appendix A, No. 4) reveals a K/Na ratio of 0.263 and Rb/Sr of 0.075, both features characteristic of relatively ancient granitic material not originating from differentiated melts, and lower than those reported by Blockley (1980) for other "older granites" of the region. The K/Rb ratio is high, but not abnormally so, (249) despite a K_2O content of only 1.2 per cent.

None of the porphyritic intrusions within the batholith has been studied in any great detail. Field observations and microscopic examination indicate that the general description of such bodies presented at the beginning of this chapter is applicable also to these intrusions, except that plagioclase is albite. The rock is generally weakly porphyritic albite adamellite containing muscovite and biotite, but muscovite is subordinate in the northwestern part of the intrusion 30 km southeast of Port Hedland. The body of porphyritic adamellite west of the Ord Range is distinctive mineralogically and chemically; it contains numerous large microcline phenocrysts in a groundmass consisting principally of oligoclase and quartz with sparse microcline and chlorite (after biotite). Both Na_2O and CaO exceed K_2O in this rock whereas the bulk of the porphyritic adamellite in the batholith is potassic. Rb/Sr ratios also differ markedly; they are about 0.1 for the Ord Range rock and between 2.5 and 5.4 for the remainder (7 samples).

The post-tectonic intrusions east and west of Tabba Tabba may be connected at depth. The western mass which crops out as rugged low hills is named the Tabba Tabba Adamellite; the eastern mass, though of larger areal extent, has somewhat less well-defined boundaries and has not been formally named.

Tabba Tabba Adamellite

The Tabba Tabba Adamellite is a post-tectonic pluton cropping out over 60 km^2 of country west of Tabba Tabba mine; it is a fine- to medium-grained albite adamellite with minor biotite and muscovite. Microcline (partly perthitic) and albite occur in approximately equal proportions, and quartz makes up about 30 per cent of the rock. The texture is xenomorphic, but there are scattered large crystals of quartz and microcline which may have been formed at an early stage.

At its eastern margin near Tabba Tabba mine, the pluton is strongly foliated parallel to the greenstone contact and contains sparse greenstone xenoliths. To the north and west, it intrudes porphyritic and migmatitic granitic rocks. By analogy with the Moolyella Adamellite the Tabba Tabba Adamellite is considered to be late Archaean.

The fact that the chemical composition of the porphyritic and post-tectonic granitic rocks of the Carlindi Batholith are similar suggests that they may be phases of a single intrusion. Though not discounted this interpretation is not adopted because the porphyritic rocks are foliated and contain less muscovite.

MUCCAN BATHOLITH

The angular eastern margin of the Muccan Batholith may reflect horsting between normal faults, but the western and northwestern contacts are intrusive. The batholith is poorly exposed in all but the northern and southeastern parts (Plate 1A) and its internal structure is imprecisely known. Migmatitic and well-foliated granodiorite and adamellite predominate, but there are also large intrusions of porphyritic adamellite. Tectonic foliation appears to be broadly concentric within the structure and crosses plutonic contacts. In the eastern part of the batholith this foliation strikes east to southeast and appears to cross the narrow Shay Gap Syncline into the Warrawagine Batholith. Two small intrusions of probable post-tectonic generation were identified in the Muccan Batholith. Approximately 15 km east of Eginbah homestead, a small stock of unfoliated, coarse-grained adamellite intrudes the contact between foliated, migmatitic granodiorite and adamellite to the south and porphyritic adamellite to the north. Relations with the porphyritic mass are uncertain but absence of foliation in the even-grained intrusion suggests that it is younger. Geochemical analysis (Appendix C, No. 14) reveals a high Rb/Sr ratio and a high K_2O content. The second intrusion occurs at the granite—banded iron-formation contact 10 km south of Shay Gap. This rock is a poorly foliated, massive, medium- to coarse-grained adamellite. Pegmatite around the mass contains considerable quantities of magnetite.

Xenolith belts, apparently structurally unrelated to adjacent synclines, occur in the eastern and northern parts of the batholith, and sheared migmatite flanks its southern margin. Another interesting feature is a suite of peridotite dykes aligned with the xenolith belts. The age of these intrusions may be similar to peridotite sills in the layered succession.

The granitic rocks of the Muccan Batholith are petrographically similar to others of their respective types in the Pilbara Block. Garnet occurs in sheared adamellite 4 km northeast of Muccan homestead, but the rock appears to be igneous rather than metamorphic.

WARRAWAGINE BATHOLITH

The Warrawagine Batholith is extensively covered by Quaternary deposits. Exposures south of Callawa homestead, and in the southern part of the mass suggest that it is almost entirely composed of foliated biotite granodiorite and adamellite. Near Callawa the rock is migmatitic, and contains numerous megascopic greenstone xenoliths. Hornblende adamellite, granodiorite and tonalite occur near the margins of the batholith, and probably reflect contamination from assimilated greenstone material. As noted above, the easterly striking tectonic foliation of the Muccan Batholith continues into the Warrawagine Batholith on the eastern side of the Shay Gap Syncline so that they may form two structural parts of a single elongate dome.

KURRANA BATHOLITH

Situated in the southeastern part of the Pilbara Block, the Kurrana Batholith is separated from the Mosquito Creek Formation to the north by a tectonic slide; on the southern side it is unconformably overlain by Lower Proterozoic rocks of the Fortescue Group. The batholith contains two principal rock types: schistose to well-foliated adamellite and massive, poorly foliated post-tectonic granite. The latter forms a discrete intrusion, and is named the Bonney Downs Granite. Plate 1A shows that the northern and southern parts of the Kurrana Batholith are composed of the older material. Schistosity is parallel to the contact with the Mosquito Creek Formation and becomes increasingly pronounced northwards. In places the rock is flaggy and primary textures have been destroyed by shear. Principal rock-forming minerals are oligoclase, quartz, microcline and minor biotite.

Bonney Downs Granite

The Bonney Downs Granite crops out over an area of about 375 km^2 centred about 25 km east-northeast of Bonney Downs homestead (Plate 1A). It has been examined at relatively few localities, chiefly near tin, tantalite and beryl deposits. In the north, the rock is a medium to coarse even-grained adamellite but in the south, near Dingo Well, microcline phenocrysts are abundant. Both types have a similar mineralogy and are composed chiefly of quartz, microcline, sodic oligoclase and chlorite (after biotite). Microcline is commonly microperthitic, and shows typical cross-hatched twinning. Chlorite has pleochroic haloes about zircon inclusions and in one sample is observed to be partly replaced by stilpnomelane. The Bonney Downs Granite intrudes the sheared and migmatitic varieties of the batholith and is unconformably overlain by Proterozoic rocks near Bonney Downs. Two samples (Appendix C, Nos. 6 and 7) are chemically typical of other post-tectonic granites in the craton.

Yilgalong Granite

The Yilgalong Granite (informally referred to as the "Elsie Creek batholith" by Noldart and Wyatt, 1962) crops out over approximately 500 km^2 around the headwaters of Yilgalong Creek. The rock is medium-grained, variably sheared biotite adamellite and granite. Shearing is most pronounced in the western and southern sections of the mass, where the foliation is orientated parallel to the intrusion's margins. Parts of the granite are mylonitized and the overall texture is that of an augen gneiss. Medium- to coarse-grained albite granite crops out over about 5 km^2 on the northeastern side of the Yilgalong Granite. The rock is rich in quartz, locally contains a weak biotite foliation and appears to intrude the main body of the granite. The Yilgalong Granite's western contact is a shear zone, its southern contact is partly intrusive, partly tectonic, and to the north and east the granite is unconformably overlain by Lower Proterozoic rocks of the Fortescue Group.

Strelley Granite

The Strelley Granite derives its name from Strelley Pool on Six Mile Creek. It consists of two distinctive units, which crop out over an area of 180 km^2. Porphyritic biotite-hornblende granite forms the central and western parts of the mass, whereas the remainder is granophyre and alkali-feldspar granite. The porphyritic variety is moderately well foliated by biotite schlieren and an alignment of feldspar phencrysts, biotite, and quartz grains. Carlsbad-twinned perthite phenocrysts are set in a hypidiomorphic granular groundmass of perthite, oligoclase, quartz, hornblende and biotite. Oligoclase is partly sericitized and rimmed by albite. Apatite, zircon and magnetite are accessory minerals. Geochemical analysis (Appendix B, No. 20) reveals that parts of the porphyritic portion are composed of relatively potassic adamellite with a high Rb/Sr ratio and anomalous tin. No cassiterite deposits have yet been discovered within the Strelley Granite.

The outer zone of the intrusion consists of medium to coarse, even-grained granophyre in the east and alkali feldsapr granite in the north. The granophyre is massive, poorly foliated, jointed and veined by quartz. Calcic oligoclase and quartz are intergrown; the rest of the rock being made up of euhedral quartz microcline and minor anhedral calcic oligoclase, perthite and chlorite. Accessory minerals are pyrite, magnetite, zircon, rutile and rare clinopyroxene. Sericitization is pervasive and other secondary minerals are calcite and epidote. The alkali feldspar granite in the northern part of the Strelley Granite is a medium- to coarse-grained, massive rock containing quartz, microcline, oligoclase, perthite, minor biotite and zircon, and the accessory opaque minerals, apatite and sphene. Zircon is unusually abundant and fluorite occupies microscopic crush zones. Secondary minerals include calcite, epidote, chlorite, rutile and rare prehnite. The texture of the rock is hypidiomorphic granular.

Within the Strelley Granite, the outer zone of granophyre and alkali-feldspar granite is intruded by the central porphyritic granite. Around its eastern margin the granophyre intrudes a distinctive, columnar jointed amygdaloidal rhyolite, and all other contacts with the surrounding greenstones are also intrusive. Several large masses of Archaean basalt enclosed by the Strelley Granite may represent roof pendants.

North Pole Adamellite

The North Pole Adamellite is an intrusive stock of medium- to coarse-grained biotite adamellite cropping out over 6 km^2 to the south of the North Pole mining centre, 40 km west of Marble Bar. The rock is massive, weakly foliated and homogeneous. Principal minerals are oligoclase (zoned), microcline, quartz and biotite. Geochemical analyses (Appendix A Nos. 26 and 27) suggest that the rock is virtually granodiorite. Combined with a low Rb/Sr ratio and general field aspect, this indicates that the rock belongs to the older granitic complex. Although its margins are intrusive, the North Pole Adamellite is considered to represent merely the uppermost part of a batholith. Bouguer anomaly patterns suggest that no great thickness of greenstones underlies the dome. Moreover, where the rock's weakly developed biotite foliation has been measured it is broadly parallel to bedding in the layered succession. This implies that the adamellite is part of a broad domal structure rather than a small vertical stock.

Satirist Granite

The geology of the Satirist Granite is imprecisely known. Fitton and others (1975, Fig. 1) considered the mass to consist of a central portion of foliated granitic rock surrounded by a wide rim of medium-grained, melanocratic granitic rock. A limited number of traverses by the writer show that the southern and central parts of the 700 km^2 batholith are composed of poorly foliated, porphyritic biotite adamellite. Photo interpretation of the eastern part of the batholith suggests that the distribution of rock types indicated on Plate 1A is correct. Well-foliated, gneissic and locally migmatitic adamellite and granodiorite crop out in the northern and northeastern sections. Microscopic examination of the porphyritic adamellite shows microcline phenocrysts in a medium- to coarse-grained matrix of quartz, oligoclase and microcline. Magnetite is an accessory mineral and secondary minerals include chlorite (after biotite) sericite, epidote and muscovite. Leggo and others (1965) computed a maximum age of 3 040 m.y. for a single specimen of porphyritic adamellite collected 1.5 km northeast of Moorambinar Pool. The reliability of this age is low however because it depends on the assumption that the rock's initial $^{87}Sr/^{86}Sr$ ratio was 0.700.

At its western contact the Satirist Granite is unconformably overlain by the Fortescue Group, but elsewhere the batholith intrudes the Archaean layered succession. Fitton and others (1975) considered that the mass is intruded by the Peawah Granodiorite, but exposure is poor in the critical area, and the two masses may be separated by a narrow belt of Archaean metasediments.

Peawah Granodiorite

The Peawah Granodiorite (Fitton and others, 1975) crops out over 200 km^2 south of Peawah mine; it is a foliated, medium-grained hornblende granodiorite. Calcic oligoclase predominates over quartz, microcline and hornblende; chlorite, actinolite, carbonate minerals, epidote, opaque minerals, zircon and apatite make up the remainder of the rock. Greenstone xenoliths are numerous along the intrusion's southern contact.

The geochemistry of the Peawah Granodiorite (Appendix A, No. 51) is similar to that of the older granitic complex of the Pilbara Block. Fitton and others (1975, p. 21) suggest that the pluton is a "younger granite" (post-tectonic) but chemistry and lithology do not support this interpretation.

Cookes Creek Granite

The Cookes Creek Granite (Noldart, 1960a, p. 141) crops out over 40 km^2 at the junction of Cookes Creek and the Nullagine River, about 45 km northeast of Nullagine. The granite is a stock intruded into Archaean basaltic rocks of the Warrawoona Group. Its margins are irregular and discordant to the bedding of the greenstones, and are intrusive on all sides. The enveloping greenstones are not visibly disrupted by the intrusion, indicating that emplacement was passive. At the southeastern contact of the mass, dykes of granitic rock intrude sandstone, gabbro and ultramafic rock. Sandstone near the contact is spotted and extensively recrystallized, apparently as a result of contact metamorphism.

The main body of the stock is a poorly foliated, coarse- to medium-grained granite or adamellite. In places it is porphyritic, and a cataclastic foliation is developed near minor faults. Some quartz veins contain fluorite and barite, and at the Cookes Creek mining centre others have been worked for wolframite and scheelite. The granite intrudes the core of a greenstone syncline and is interpreted (Hickman, 1975b) as a post-tectonic intrusion. Microscopic examination reveals masses of anhedral quartz up to 6 mm across, smaller subhedral to anhedral prisms of albite (An_5) and abundant interstitial microcline. Subordinate biotite is chloritized and albite is slightly sericitized. The chlorite is associated with accessory zircon and secondary sphene and fluorite. Fluorite also occurs with minor carbonate in fractures and shears. Porphyritic varieties contain euhedral microcline crystals up to 20 mm long, oligoclase, quartz and minor biotite with accessory apatite, zircon, sphene, epidote and metamict allanite. De Laeter and others (1977) dated the Cookes Creek Granite at about 2 600 m.y. based on a compromise between the total rock age of 2 568 ± 37 m.y. (initial $^{87}Sr/^{86}Sr$ ratio of 0.7307 ± 0.0097) and a biotite age of 2 700 m.y.

GREGORY GRANITIC COMPLEX

The Gregory Granitic Complex extends almost 100 km along the eastern margin of the area shown on Plate 1A. Noldart and Wyatt (1962) included this unit within the "Gregory Range Granite" and regarded it as Proterozoic, but mapping by the Geological Survey in 1973 led to a revision of the area's geology (Hickman, 1975a). The "granite" was found to consist of felsic lava, belonging to the Fortescue Group, granophyre and several different types of granitic rock. Each of these rock types is broadly restricted to particular parts of the 10 km wide belt, suggesting that either they represent distinct zones within a heterogeneous intrusion or they form individual masses. All units except the felsic lava are collectively referred to as the Gregory Granitic Complex.

Discussion of the Gregory Granitic Complex has been delayed until now because there are grounds to question whether it forms part of the Pilbara Block or part of the Paterson Province. Blockley and de la Hunty (1975) included it in the Paterson Province, but explained that tectonically it represents an eastern continuation of the Pilbara Block. The southern part of the complex is composed of sheared granite and adamellite similar to that within the Kurrana Batholith. De Laeter and others (1977) dated samples of this rock collected near Lookout Rocks at 2 651 ± 60 m.y. At this locality, the rock is pink, medium- to coarse-grained gneissic granite and adamellite with thin dark streaks of biotite and hornblende enclosing feldspar crystals up to 10 mm in diameter. Potassic feldspar exceeds oligoclase and accessory minerals including sphene, apatite, zircon, fluorite and opaques. Quartz is streaked out into complex wisps and ribbons, and the feldspars are broken down into smaller grains in which twin lamellae are kinked or bent. Even the biotite is strongly broken and twisted.

Farther north these sheared granitic rocks grade into less deformed rocks containing hastingsitic hornblende. Microscopic examination still reveals shear and recrystallization however. The rock is typically fine to medium grained and forms massive outcrops. In hand specimen it bears some resemblance to granophyre that crops out farther to the north, but its texture is not granophyric. The hornblende granite is unconformably overlain by the Middle Proterozoic Yeneena Group to the east but poor exposures makes relations with adjacent granitic rocks uncertain. To the north of the hornblende granite is an area of alkali feldspar granite locally containing bands rich in martite. On the western side of the complex there are several exposures of rock resembling rapakivi granite. Composite ovoids of microcline or oligoclase aggregates measuring up to 20 mm in diameter are separated by a dark, fine-grained matrix rich in biotite and hornblende. Anhedral perthitic microcline phenocrysts locally comprise up to 50 per cent of this rock. Other minerals, apart from oligoclase, are quartz, opaques, sphene, zircon and accessory apatite, metamict allanite and muscovite. The present interpretation of the rock is that it is a sheared porphyritic variant of the granophyre.

Ragged Hills Granophyre

The Ragged Hills Granophyre crops out intermittently over an area of approximately 500 km^2 along the eastern side of the Gregory Range. Ragged Hills mine is situated approximately 8 km west of the type area which is easily accessible on the southern side of the road linking Ragged Hills and Telfer. The rock is a pink, medium-grained granophyre containing scattered rounded phenocrysts of perthite in a granophyric matrix. Mafic minerals are biotite, hornblende and aegirine augite. Accessory minerals include allanite, zircon, tourmaline and opaque minerals. Much of the intrusion east of Ragged Hills is a massive rock but elsewhere cataclasis is common and the granophyre contains a steeply inclined tectonic foliation.

The age and relations of the Ragged Hills Granophyre have yet to be firmly established. Preliminary geochronology by J. R. de Laeter indicates that the rock is about 2 400 m.y. old. Similarities of chemistry and mineralogy between the granophyre and felsic lava to the west suggest that the intrusion may represent a high-level feeder. The contact between the granophyre and the felsic lava succession is either tectonic or gradational. Because the lava conformably underlies the Kylena Basalt of the Fortescue Group it is designated as Lower Proterozoic in age; this in turn suggests that the Ragged Hills Granophyre is also Proterozoic. On the other hand, the rock is somewhat similar to the foliated hornblende granite in the southern part of the complex which at present is thought to be Archaean. Further geochronology is planned.

OTHER BATHOLITHS

Batholiths such as the Caines Well Granite, Harding Granite, Balla Balla Granite, Portree Granite, Chiratta Batholith and Karratha Batholith in the west Pilbara are all very poorly exposed, and it is uncertain to what degree rocks which crop out are representative of those underlying the plains. Beyond the general statement that these masses appear to be essentially composed of rocks belonging to the older complex (i.e. foliated granodiorite and adamellite with local porphyritic bodies), no systematic description appears warranted. Certain interesting features are noted below.

The best exposed and most complex part of the granitic terrain in the west Pilbara is situated southwest of Roebourne. In this area granitic rocks have invaded the Archaean layered succession to produce a broad zone of migmatite. Ryan (1966) referred to these rocks as metasomatized and hybrid rocks containing recognizable relics of the Roebourne Group. Many of the rocks are sheared, even to the point of mylonitization. This is especially true in the vicinity of the Sholl Shear Zone which, on the basis of apparent displacement of various rock units, is interpreted as a major sinistral wrench. A shear zone that separates the Harding and Balla Balla Granites from the Caines Well Granite is regarded as a continuation of the Sholl Shear Zone. Sheared granitic rocks exist near the southern margin of the Caines Well Granite, near the southern margin of the Karratha Batholith and within the Chiratta Batholith near Chiratta homestead. In each locality, the shear foliation is aligned to the nearby batholith margin, suggesting at least a partial relationship to diapiric uplift. De Laeter (pers. comm.) dated samples of the Caines Well Granite collected from exposures in the Sherlock River, 25 km west of Mons Cupri, at 2 700 m.y. (initial $^{87}Sr/^{86}Sr$ ratio 0.705). De Laeter considers that the age computed is that of the last major metamorphism, pointing to similar metamorphic ages obtained by Oversby (1976) in the east Pilbara.

Northwest of Dampier at the northern contact of the Karratha Batholith, granite samples collected close to the Proterozoic Gidley Granophyre (intrusive along the unconformity between the granite and the Fortescue Group in this area) show marked effects of partial remelting. Coarse, embayed quartz grains are separated from very coarse-grained potash feldspar by broad areas of granophyre. Plagioclase is subordinate, occurring as euhedral inclusions in potash feldspar. Contact metamorphism imposed on the granite has recrystallized the rock, or at least produced new textures such as erratic perthitic exsolution lamellae. Sheaves of tridymite are common and cryptocrystalline stilpnomelane is present.

SEDIMENTARY ROCKS

Clastic and chemically precipitated sedimentary rocks make up most of the Gorge Creek Group, which forms the upper half of the Pilbara Supergroup. The Warrawoona Group contains numerous thin chert units but is principally composed of volcanic rocks.

Sedimentary cyclicity, such as that recognized in the Moodies Group of the Barberton Mountain Land (Anhaeusser, 1971), is not a feature of the Gorge Creek Group. Sandstone at the base of the Gorge Creek Group passes upwards into shale and banded iron-formation but no greywackes have been identified at this level. Moreover, basalt intercedes between the banded iron-formation and overlying sandstone and conglomerate. The latter passes upwards into a mixed sedimentary assemblage of sandstone, siltstone, shale and greywacke. This transition, preserved in only a few areas of the Pilbara Block, is the only part of the succession bearing a resemblance to Anhaeusser's (1971) cycle.

Plate 1A shows five types of clastic sedimentary rock (one of which is an unsubdivided unit) and two varieties of chert. The most widespread are schistose, psammitic and pelitic types (including derivatives of greywacke and rocks deposited from turbidity currents), but sandstone containing conglomerate also forms much of the succession.

SEDIMENTARY ROCK (NOT SUBDIVIDED)

Units falling into the unsubdivided category consist principally of rapidly alternating lithologies. The largest outcrops occur southwest of Corunna Downs, west of Spear Hill, at Croydon and east of Karratha.

Southwest of Corunna Downs homestead the centre of the Coongan Belt is occupied by psammopelitic and pelitic schist with subordinate quartzite and chert. Some of the sediments are ferruginous, although it is uncertain to what extent this feature is primary. In the southern part of the belt the rocks change facies to become more psammitic and pass upwards into ferruginous sandstone and shale. All these beds are assigned to the Corboy Formation (Table 2) which elsewhere is overlain by banded iron-formation of the Cleaverville Formation. The upward change in lithology to ferruginous strata may represent a sedimentary transition.

Alternating beds of sandstone, siltstone and shale crop out on the eastern side of the North Shaw Belt 10 km west of Spear Hill. Here also many of the sediments are ferruginous but there is no passage into iron-formation. At Croydon the centre of a northerly plunging anticline rimmed by sandstone and conglomerate is occupied by pelitic schist underlain by amphibolite, whereas near the Lower Nickol centre, 15 km east of Karratha, schistose arenaceous sedimentary rocks underlie chert units correlated with the Towers Formation (includes Marble Bar Chert Member). The original composition of these rocks is difficult to establish because of cataclasis and silification, but tuff, greywacke, sandstone and chert appear to be represented.

Sedimentary units too thin to be shown on Plate 1A occur in numerous areas. The oldest beds form part of the Talga Talga Subgroup and include black shale at Shark and ferruginous sediments in the McPhee Formation at Talga Talga mining centre. Shale and sandstone form part of the Salgash Subgroup at Salgash and interbedded sandstone, tuff, shale and chert occur within the same unit at North Pole.

FERRUGINOUS CLASTIC ROCKS

Ferruginous clastic sedimentary rocks associated with ferruginous chert and banded iron-formations crop out across large tracts of country at Soanesville, Cooke Bluff Hill, Shay Gap, Strelley, the Ord Range, Kangan, Station Peak and in the Pilgangoora Syncline. Ferruginous shale, siltstone, sandstone and chert form a lithogenetic association chiefly developed in the lower part of the Gorge Creek Group. The various rock types alternate rapidly and cyclicity is commonly present. On a larger scale, the ferruginous sediments are generally underlain by non-ferruginous sandstone and siltstone, and overlain by ferruginous chert and banded iron-formation. The lithology appears to mark a transition from high-energy conditions to phases of fine clastic and chemical precipitation from slowly circulating water.

SILTSTONE AND SHALE

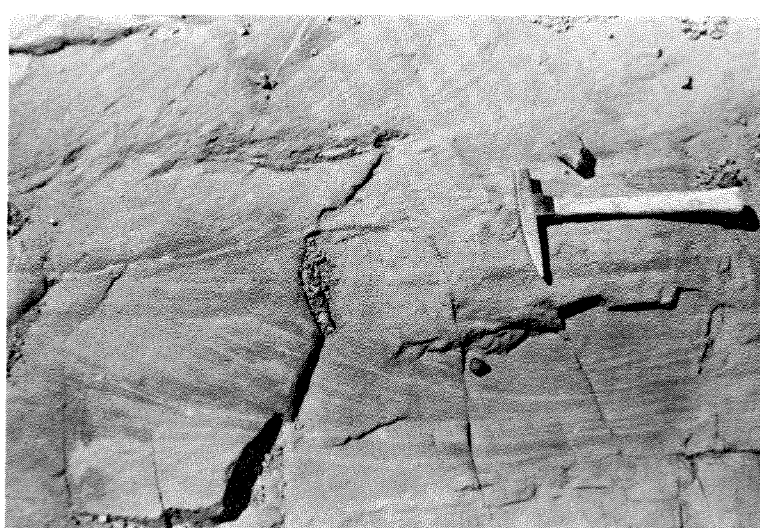
Pelitic, semipelitic and fine-grained psammitic rocks form a wide, east-west trending outcrop in the centre of the Mosquito Creek Synclinorium. Here, and to the southwest of Croydon, the rocks represent distal turbidite units within generally more psammitic successions. Well-bedded siltstone with minor shale intercalations forms part of the Gorge Creek Group in the Soanesville area. Cross-bedding, graded bedding, ripple marks, scour marks and slump folds are preserved at some localities. Certain of the rocks at Soanesville are unusually dark, graded and possess a high lithic content, suggesting deposition from turbidity currents.

SANDSTONE AND CONGLOMERATE

Sandstone, quartzite and conglomerate constitute a major part of the Gorge Creek Group. The sandstone and quartzite units are bedded at intervals of 0.1 to 1.0 m and exhibit cross-bedding (Fig. 6) and, more rarely, ripple marks. Conglomerate usually occurs as thin pebble beds but in places coarse cobble conglomerate, tens of metres in thickness, are developed. The pebbles are sub-rounded to rounded and consist of quartzite, chert, vein quartz, felsic lava, basalt, serpentinite and rare granite. The presence of granite clasts in the Gorge Range establishes that granitic terrain was exposed to erosion during deposition of the Gorge Creek Group. Conglomerate is well exposed in Shaw Gorge, Budjan Creek, Eastern Creek, McPhee Creek, and the Gorge Range. All the conglomerate units are lenticular and change thickness laterally. At some localities they overlie unconformities but they are generally intraformational.

Sandstone is normally medium to coarse grained and variably recrystallized and silicified. Feldspar content is generally low, the rock being composed chiefly of rounded grains of quartz and minor chert. Clay minerals are replaced by secondary mica.

Cross-bedding in the Lalla Rookh Sandstone west of North Pole suggests that the Archaean palaeocurrent direction was locally south to north. The depositional environment of the rocks is considered to be fluviatile, deltaic or shallow water marine.



GSWA 19003

Figure 6. Cross-bedding in the Lalla Rookh Sandstone 8 km southwest of Strelley Pool.

The Lalla Rookh Sandstone varies in thicknes up to 5 000 m. Lateral variations in thickness suggest deltaic deposition, but the formation persists across most of the Pilbara Block. The relatively thin parts of the formation may represent platform sands.

SCHISTOSE PSAMMITIC TO PELITIC ROCKS

Clastic rocks ranging in composition from sandstone to shale, but chiefly composed of rock detritus rather than mineral fragments, crop out in the Mosquito Creek area of the east Pilbara, and the Mallina district of the west Pilbara. The total

Figure 7A. Photomicrograph of sheared conglomerate in the Mosquito Creek Formation 17 km east of Mosquito Creek. Elongated clasts of quartz, chert and altered lava are set in a fine-grained matrix. Plane polarized light. GSWA 32630.

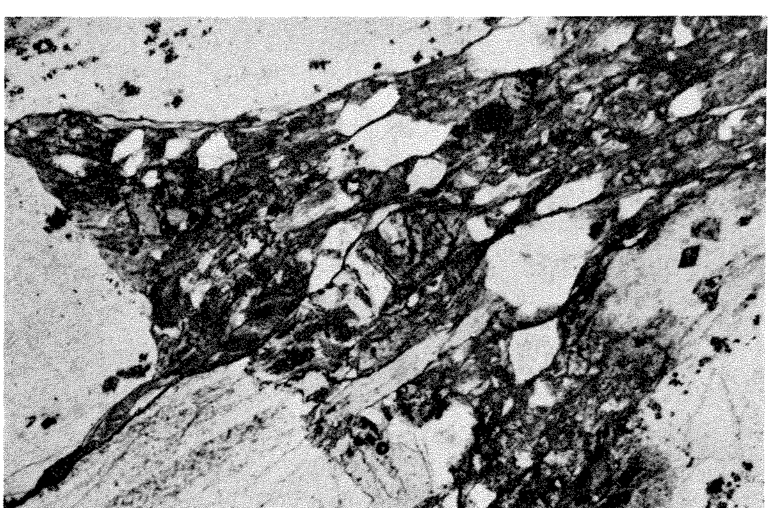


Figure 7B. Above, at greater magnification showing microscopic cataclastic texture.

outcrop area (including superficial deposits) is approximately 7 000 km^2 and the true stratigraphic thickness of the formation (Mosquito Creek Formation) in which they occur is approximately 5 000 m. Because the sediments are poorly sorted (a large proportion are turbidites) and contain a large clay component, metamorphism has transformed them into schist. In most exposures the principal foliation of the rock is not bedding but a schistosity parallel to mica alignment. Consequently, where bedding planes are indistinct due to lithological homogeneity or absence of rapid vertical variations in grain size, the true attitude of the strata is difficult to determine; schistosity may be vertical where bedding is horizontal.

The dominant rock type is schistose micaceous siltstone and sandstone interbedded with more pelitic units, and rare conglomerate (Fig. 7A & B). Graded bedding, cross-bedding, scour structures and Bouma cycles (generally incomplete) are exposed on weathered rock platforms and provide valuable facing evidence. Between Nullagine and Mosquito Creek repeated reversals of facing are observed on traverses across strike. Since bedding is steeply inclined, isoclinal or sub-isoclinal folding about east-west axes must be present. Good exposures of sedimentary structures in the Mosquito Creek Formation are accessible on the eastern side of the Great Northern Highway 2 km south of Nullagine opposite the turn-off to Garden Pool.

The petrography of the schistose psammitic and pelitic rocks is similar to that of greywacke. Mineralogy varies according to facies and provenance, and all the rocks are metamorphosed. Angular to sub-rounded grains of quartz, feldspar and rock (generally chert) are loosely packed into a fine groundmass of quartz, feldspar, sericite, chlorite and carbonate minerals. Iron staining is a common feature.

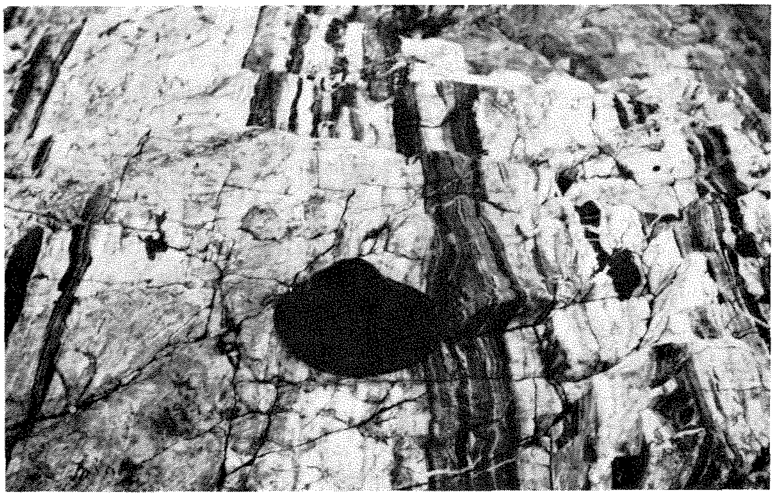
Ryan and Kriewaldt (1964) noted that concordant bodies of quartz-feldspar porphyry are found in many parts of the west Pilbara succession. The greywacke contains abraded and strained feldspar of a type identical with that in the porphyry suggesting syndepositional erosion and reworking.

East of Nullagine amphibole schist close to the southern margin of the Mosquito Creek Formation contains scattered fine grains of quartz and feldspar. Detritus was probably derived by erosion of the Warrawoona Group which the Mosquito Creek Formation unconformably overlies.

CHERT

Chert occurs throughout the Pilbara Supergroup but is most widespread in the Warrawoona Group. Grey, white and red banding at intervals of 1 mm to 10 mm is developed in most of the units, but others are entirely pale grey, green or black. Banding appears to be caused by the presence of submicroscopic inclusions of hematite and other minerals, generally in very low concentration. Because the chert is cryptocrystalline grain-size grading is not normally discernible. However graded beds have been noted in silicified tuff associated with chert in the Towers Formation about 10 km northwest of Marble Bar. Colour grading is poorly developed and its significance is not properly understood.

The Marble Bar Chert Member is a strikingly beautiful red and white chert, which at Marble Bar Pool forms a rock bar across the Coogan River, 3 km west of Marble Bar (Fig. 8). Brecciation of the banded chert (Fig. 9) at this and other localities may have resulted from slumping or diagenetic processes.



GSWA 19006

Figure 8. Banded chert of the Towers Formation at Marble Bar Pool.

GSWA 19007

Figure 9. Brecciated banded chert at Marble Bar Pool.

Angular blocks of banded chert are set in an amorphous dark grey chert matrix, presumably injected from liquid parts of the siliceous gel. No tests have been made to determine any compositional differences between the grey and white chert, but it is possible that such differences are minor; colour may partly reflect molecular structure. Mobilized chert units which intrude joints and faults at localities such as North Pole (Hickman, 1973) are invariably dark grey, perhaps because of a relatively disordered internal structure. Red and white banded chert such as that at Marble Bar Pool occurs in several areas and at several stratigraphic positions, but generally it is uncommon in the Pilbara Block. The distinctive red banding terminates abruptly laterally so cannot be used as a diagnostic feature in stratigraphic correlation. Green chert occurs at Warrawoona, Eastern Creek, Gallops Well, Box Well, Talga Peak, Pear Creek and Mount Regal. This type of colouration probably reflects the presence of pale green chromian muscovite (fuchsite) or iron minerals. Black chert, containing carbonaceous material and/or finely disseminated pyrite, crops out in Spinaway Creek 4 km east-northeast of Spinaway Well, in Chinaman Creek 3 km north of Marble Bar Pool, and at Yandicoogina.

Sedimentary chert may be formed in several ways:

(1) by precipitation of microscopic siliceous organic remains such as diatoms and radiolaria;

(2) by metasomatic replacement of limestone or other sedimentary rock; or

(3) by inorganic precipitation of colloidal silica.

No relics of pre-existing sedimentary rocks have yet been identified in the Archaean cherts of the Pilbara Block. Dunlop and others (1978) reported organic spheroids at North Pole but no firm identifications have yet been possible. This largely negative evidence, coupled with the close association of chert with pillow basalt and felsic lava, suggests that most of the units originated as silica gels; precipitation probably occurred where magmatic solutions enriched the water in silica. Contamination by hematite, carbon, pyrite, and chromium minerals was probably controlled by slight changes in Eh, pH and geological setting (e.g. chromium was derived from nearby ultramafic bodies).

BANDED IRON-FORMATION AND FERRUGINOUS CHERT

Banded iron-formation (BIF) in which iron minerals make up about 50 per cent of the rock is chiefly confined to the lower part of the Gorge Creek Group, although thin units occur also in the Talga Talga Subgroup near McPhee Reward and in the Mosquito Creek Formation west of Station Peak. BIF is generally dark grey or black, but some units are of the red and black banded variety known as jaspilite. Jaspilite consists of red jasper and iron oxides banded at between 5 mm and 10 mm intervals. Examples of this type of rock are exposed at Strelley Pool, Blue Bar, Western Shaw, Copper Hills (5 km east), North Pole (7 km north), Paddy Market Gorge, Lionel (6 km north), Coppin Gap, Mount Cecilia, Shay Gap, Goldsworthy, the Ord Range and Cleaverville. Across the Pilbara Block in general, however, jaspilite is subordinate to black-brown BIF. In this type of rock layers of specular hematite predominate over layers of ferruginous chert, hematite generally being the overall main constituent. Well-defined microbanding and mesobanding (defined by Trendall, 1975a) are rarely observed. In some areas BIF appears to pass down-dip into ferruginous shale suggesting that surface silicification and iron enrichment have produced certain varieties of the rock. Iron ore bodies mined at Goldsworthy and Shay Gap are believed to have formed by supergene enrichment, ore grade being about 64 per cent Fe. Further information is provided by Brandt (1964, 1966) and Matheson and others (1965).

Approximately 30 km south of Port Hedland metamorphosed BIF is exposed near Bullen Hill. The rock is now a sheared quartz-magnetite-grunerite rock with minor chalcedony and apatite. Magnetite occurs as euhedral to subhedral crystals up to 2 mm across and is associated, in ill-defined bands, with subhedral polysynthetically twinned grunerite.

The continuity of the formations on a regional scale and the continuity of microscopic layers along strike justify the conclusion that the iron-formations were deposited in extensive marine or freshwater basins under low energy conditions. Coarse detritus and current structures are always absent. Kimberley (1978) presented a classification of iron-formations "based on a palaeoenvironmental interpretation of the physical characteristics of ironstone in the iron-formation and the characteristics of associated rocks". On this classification the BIFs of the Pilbara Supergroup are of MECS-IF, SVOP-IF and DWAT-IF types. MECS-IF is said to have been deposited in extensive shallow continental shelf environments adjacent to low-lying continents. SVOP-IF is regarded as indicative of more localized deposition in shallow water over eroded volcanic centres. DWAT-IF is a iron-poor, deep-water deposit associated with turbidites. In general BIF in the Warrawoona Group is of SVOP-IF type. In the Gorge Creek Group BIF is of MECS-IF type except in the Mosquito Creek Formation (e.g. at Mount Langenbeck and Station Peak) where it more closely resembles DWAT-IF.

The chert fraction of the iron-formations probably formed as a siliceous gel or ooze, but the vast amount of iron precipitated is more difficult to explain. Theoretically, the iron may have been derived by weathering of mafic rocks or by upward passage of iron-bearing water into the depositional basin. Trendall (1965b) pointed out that the quantity of iron required for the Brockman Iron Formation (Hamersley Group) is so great as to render the weathering process hypothesis virtually untenable; for example, such a process would have released vast quantities of aluminium, yet no alumina-rich deposits are associated with the iron formations. Hough (1958) considered that many banded ferruginous chert units were deposited in large freshwater lakes, low in nutrients and having a well marked density stratification during the warm season. During the warm season the lower water layers were slightly reducing and acidic so that, whereas silica in solution was precipitated, iron remained in solution. During the cold season, complete circulation of water was restored, density stratification disappeared, and under oxidizing and alkaline conditions iron minerals were precipitated. In discussing the origin of the Brockman Iron Formation, Trendall and Blockley (1970, p.276) concluded that iron was derived magmatically and precipitated in water-rich colloidal forms according to seasonal variations. During compaction the precipitated iron minerals recrystallized to adopt their present form. Hem and Cropper (1959) stated that the amounts and kinds of dissolved ions or molecules containing iron in the ferrous and ferric states are related to the pH and Eh of the water in which they occur. Groundwater not exposed to air has low Eh and pH, if enough CO_2 is present. Under these conditions ferrous solutions containing 50 ppm Fe are permanently stable. As such water reaches the surface it dissolves oxygen from the air, becomes less acidic and precipitates ferric hydroxide. Hem and Cropper demonstrated this process using spring water.

The general association of volcanic rocks and BIF in the Pilbara favours derivation of iron from magmatic water, and perhaps from iron-rich groundwater expelled during cooling and compaction of underlying volcanics.

FELSIC VOLCANIC ROCKS

Felsic volcanic rocks are concentrated at four stratigraphic levels in the Pilbara Supergroup, namely in the Duffer Formation, Panorama Formation, Wyman Formation and the Mons Cupri Volcanics (Plates 1A and 1B and Table 2). In general the lower two formations are dacitic whereas the others are predominantly rhyolitic.

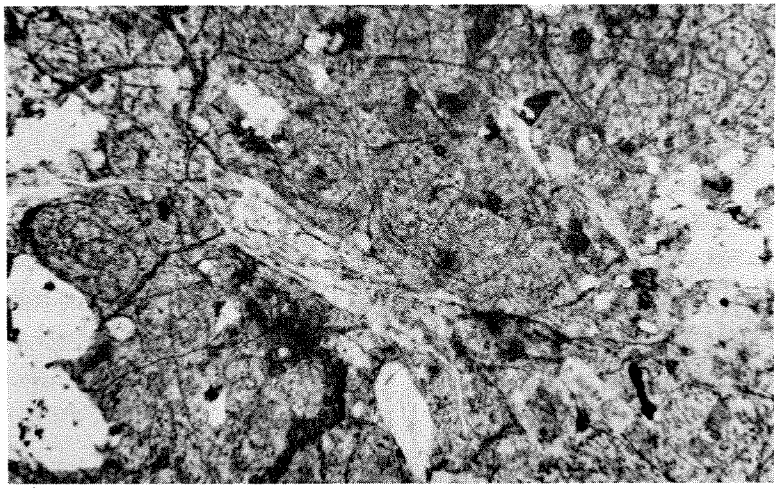
Pyroclastic rocks are distinguished (Plate 1A) in areas where they form the bulk of the succession, but most outcrops are composed principally of lava or intercalated lava flows and pyroclastic deposits. Preservation of igneous textures and mineralogy is good except in tectonically attenuated parts of the greenstone belts where the felsic volcancis have been transformed into quartz-sericite schist. Shear is locally so advanced that it becomes difficult to distinguish felsic volcanic and sedimentary units. Penetrative dynamic modification is accompanied by increased metamorphic grade (to amphibolite facies) and mineralogical and chemical alteration with the result that microscopic examination and chemical analysis may also fail to resolve problems of identification. Fortunately, such extreme alteration is fairly uncommon and primary lithology can generally be determined.

FELSIC LAVA

Dacite and rhyolite lava is massive, columnar jointed or more rarely pillowed, and is commonly porphyritic, spherulitic, perlitic (Fig. 10), amygdaloidal and flow-banded. Most outcrops are craggy and range in colour from pale grey (generally dacite) to reddish orange, but felsic schist forms pale salmon-pink ridges, commonly buttressed by chert or quartz veins. Easily accessible exposures of felsic lava are located between Marble Bar and the Coongan River, and at Camel Creek close to the Marble Bar-Corunna Downs road. At this last locality an excellent example of columnar rhyolite in the Wyman Formation (Fig. 11) may be examined about 3 km east of the creek crossing (a four-wheel-drive track leads directly to the outcrop). In the west Pilbara the best exposed and most accessible felsic volcanics crop out at Mons Cupri, about 5 km southwest of Whim Creek.

The petrography of the felsic lava flows is relatively simple. Porphyritic varieties contain quartz and feldspar phenocrysts (euhedral or corroded) up to 3 mm in diameter set in a fine-grained to glassy and variably sericitized, saussuritized, chloritized, carbonatized and silicified quartzo-feldspathic groundmass. Potash feldspar phenocrysts in rhyolite are commonly perthitic and probably represent anorthoclase which has been inverted to microline and exsolved sodic plagioclase. Plagioclase generally ranges in composition from albite to andesine and microcline is variable according to overall composition. In many instances small plagioclase microlites define a flow banding. Biotite, amphibole, pyroxene, zircon and sphene are minor accessories. Secondary minerals not mentioned above include paragonite (east of North Shaw mining centre), piedmontite (north of Marble Bar) epidote, rutile, tourmaline, tremolite, phengite, barite and fluorite.

Lipple (1973) presented a detailed description of pillow dacite within the Salgash Subgroup (probably part of the Panorama Formation) in a tributary of Dalton Creek, about 7 km east-southeast of Soanesville. The pillows have convex upper surfaces and concave of flat basal margins, often with drape structures including 'tails', and range in size up to 4 m long and 1 m thick. The rock is pale grey and contains numerous thin veins of chalcedony. Pillow skins are fine-grained to glassy and separate interpillow material from a marginal pale grey zone containing numerous vesicles and amygdales. The interpillow material is a mixture of felsic tuff and grey chert, the latter probably having been forced upwards from underlying siliceous gel. Some chert may have been precipitated simultaneously. All the pillows are non-variolitic. In thin section, microphenocrysts of euhedral to subhedral plagioclase are partly sericitized; X-ray



1mm GSWA 19008

Figure 10. Photomicrograph showing perlitic texture and quartz phenocrysts in flow-banded rhyolite of the Wyman Formation at Budjan Creek. Plane polarized light. GSWA 49362.

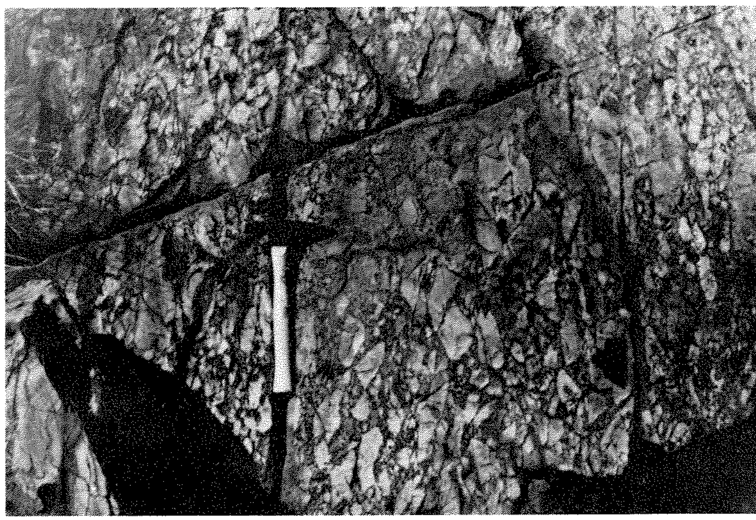
GSWA 19009

Figure 11. Columnar rhyolite of the Wyman Formation at Camel Creek, 16 km south of Marble Bar.

diffraction examination of the plagioclase indicates that it is probably oligoclase. The groundmass consists of elongate feldspar crystallites (0.25 mm long) forming a relict hyalopilitic texture within a devitrified cryptocrystalline matrix. Part of the matrix is composed of well-developed feldspar microlites, locally forming spherulitic masses separated by mosaic quartz and actinolite. Leucoxene, sphene and minor magnetite are the accessory minerals. Secondary minerals include prehnite (more abundant near pillow margins), calcite and chalcedony.

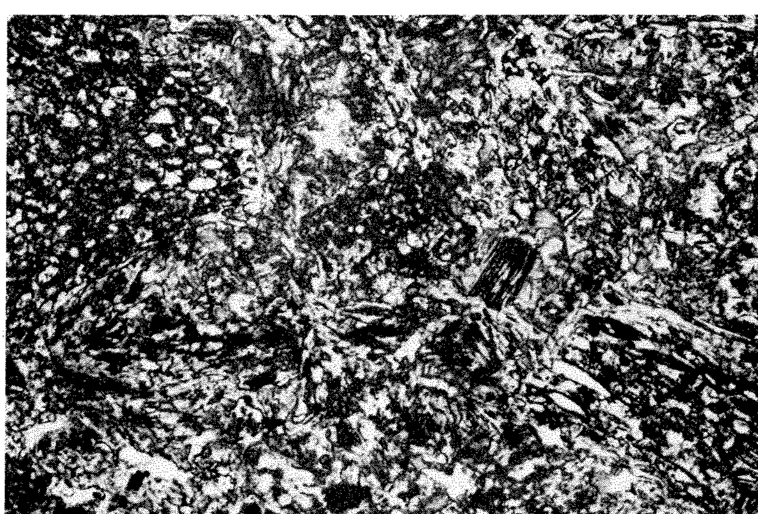
AGGLOMERATE AND TUFF

Thick units of felsic agglomerate and tuff occur at McPhee Creek, Kelly, Copper Hills, Sandy Creek, Shark, Marble Bar, Six Mile Creek, Mons Cupri and Mount Sholl. Angular clasts of felsic lava and less commonly chert, measure up to 0.2 m in the agglomerate units. Blocks many metres in diameter occur in the McPhee Creek area, but these are exceptional. The rocks are massive, except where sheared, and clasts are set in a groundmass of tuff and/or lava (Fig. 12). Alteration is similar to that in the lava units. Good exposures of dacitic agglomerate are accessible at the northern end of the



GSWA 19010

Figure 12. Felsic agglomerate of the Duffer Formation at Sandy Creek, 35 km southeast of Marble Bar.

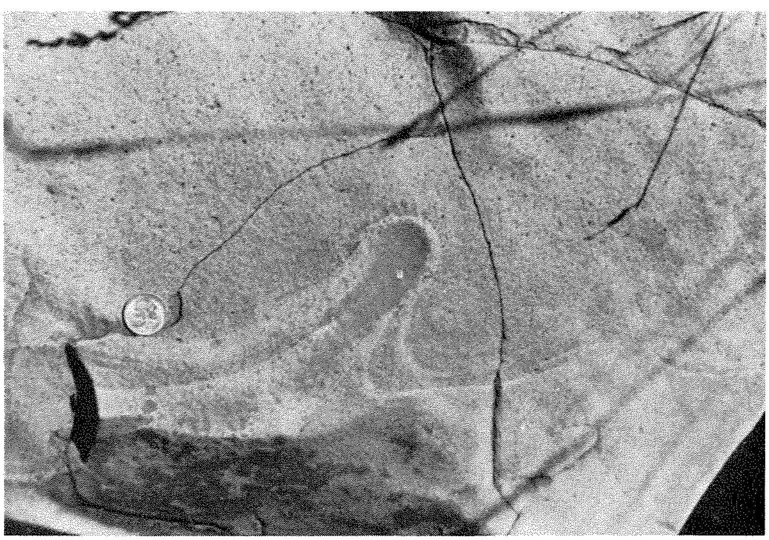


1mm GSWA 19011

Figure 13. Photomicrograph of dactitic ignimbrite from the Duffer Formation at Bowls Gorge, 14 km north of Marble Bar. The rock contains devitrified glass shards with fragments of pumice and lava. Plane polarized light. GSWA 49294.

picnic area at Chinaman Pool. Here the rocks, which locally form the upper part of the Duffer Formation, contain not only lava fragments but also clasts of red chert derived by explosive cannibalization of the underlying pile. Similar rocks are exposed farther north in the banks of the Coongan River, and also at the old railway crossing over Duffer Creek, 10 km north of Marble Bar (two-wheel-drive vehicles can reach both localities).

Felsic tuff and ignimbrite units occur at Copper Hills, Kelly, Marble Bar, Soanesville, McPhee Creek, Mons Cupri and the Lower Nickol Mining centre. The Copper Hills unit was included in the Copper Hills Porphyry by Noldart and Wyatt (1962) who regarded it as an intrusive rock. Although the rock is considerably weathered, bedding is preserved and agglomerate is present. Microscopic examination of such rocks shows shards and pumice (Fig. 13). De Laeter and Trendall (1970) dated samples from Copper Hills mine at 2 880 ± 66 m.y., but this result probably represents the age of the last major metamorphic event rather than the true age of the rock. Felsic tuff is generally dacitic in composition. Plagioclase and quartz fragments up to 3 mm across typically comprise about 50 per cent of the rock, the remainder being a dusty groundmass. Devitrified glass shards and pumice fragments are common and sedimentary structures include poorly developed cross-bedding and diagenetic injection structures (Fig. 14).



GSWA 19012

Figure 14. Diagenetic injection structure in bedded dacitic tuff of the Duffer Formation, Bowls Gorge.

As noted in the introduction to this chapter, the felsic volcanic rocks form wedge-shaped bodies rather than tabular piles typical of the mafic lavas (see also Plate 2). This feature is attributed to viscosity differences and the fact that felsic volcanics make up a relatively minor proportion of the total Archaean volcanic pile. Felsic volcanism was largely restricted to centres at Marble Bar, Copper Hills, McPhee Creek, Honeyeater Creek, Mons Cupri and the Mount Sholl-Whundo area.

MAFIC VOLCANIC ROCKS

Mafic volcanic rocks crop out over about half the total area occupied by the Pilbara Supergroup. Basalt and high-magnesium basalt, in most areas massive, but commonly pillowform and variolitic, vesicular and amygdaloidal, form thick and regionally extensive units at many stratigraphic levels. Except in the Whim Creek area and in the lower part of the Duffer Formation, andesite is very uncommon, and rocks, which in the field appear to be of intermediate composition, are generally altered basalt. Hallberg (1970) noted a similar absence of andesite in the Norseman-Lake Lefroy-Coolgardie area of the Yilgarn Block. Basaltic tuff and agglomerate are encountered in the Duffer Formation west of Marble Bar, at the top of the Mount Ada Basalt 25 km north of Marble Bar and also in the Shady Camp Well area, but elsewhere such rocks are extremely rare.

BASALT

Pillow basalt appears to be far more common in basalts of the Pilbara Block than in those of the Yilgarn Block. The pillow structures generally fit closely together and are separated by interstices filled by dark, aphanitic material. They range in size up to about 3 m in diameter and 1.5 m in vertical depth. Cross-sections are variously lenticular, planoconvex and concavoconvex and in three dimensions the structures are discoid, balloon like, sausage shaped or T-shaped. Stratigraphic tops are generally convex whereas bases are flat, concave or form cuspate 'tails' (Fig. 15). Some pillows appear to have burst shortly after formation and are connected to smaller pillows formed by the exuded lava. Radial jointing is common and varioles and vesicles are clustered close to pillow margins, tending to be most numerous in the upper parts (a feature also noted by Henderson, 1953). Vesicles are commonly elongate or tubular, long axes radiating from the pillow cores, and may be partly or completely filled by quartz, chalcedony or calcite. Each pillow possesses a chilled, grey-green crypto-

GSWA 19013

Figure 15. Pillow structures in the Apex Basalt at Sandy Creek, 40 km southeast of Marble Bar. Vesicles are concentrated near the upper (convex) margins. 'Tail' structures confirm that facing is from right to left.

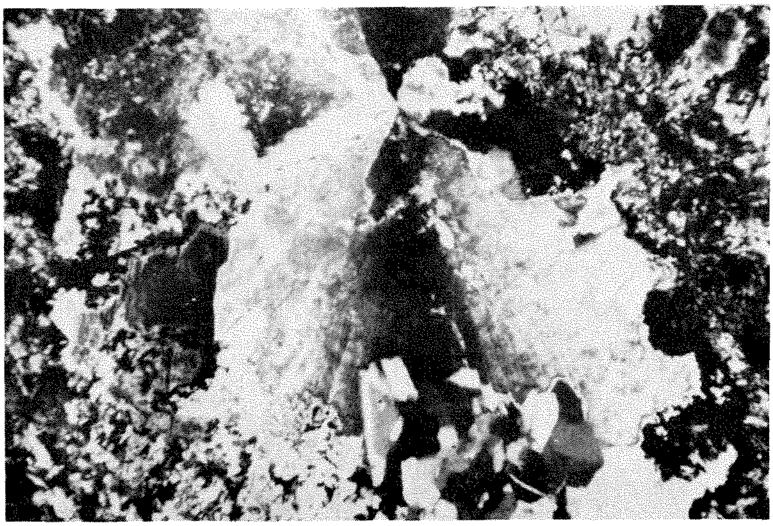
crystalline 'skin' about 2 to 10 mm thick. On its outer surface this skin may be smooth, spotted with spherules or polygonally cracked. Grain size increases towards the cores which consist of acicular amphibole and xenoblastic plagioclase. On weathered surfaces pillow cores are normally the darkest parts of the structures, but pale spotting is produced by patchy concentrations of feldspar. Interstitial material occupying the spaces between the pillows is composed of cryptocrystalline chloritic rock, palagonite, chert or altered tuff.

Geochemical analysis shows that the pillow lavas are not spilitic in composition, but range between tholeiitic and komatiitic. Easily accessible exposures of pillow basalt are available at Marble Bar Pool, McPhee Reward mine (Talga Talga mining centre), Shay Gap (2 km west), Cleaverville and at several points on the Great Northern Highway north of Lionel and west of Farrell Well. Less accessible exposures are ubiquitous, some of the most impressive being at Warrery Gap, Sandy Creek, Chinaman Creek and Soanesville.

Flows of massive basalt can be difficult to distinguish from sills of dolerite; indeed the distinction is probably not important because most of the sills appear to be cogenetic and penecontemporaneous with the surrounding volcanics, an interpretation supported by geochemistry. Systematic traverses across basalt formations have revealed that, on the basis of petrographic criteria, up to 30 per cent of such formations is composed of stratiform dolerite or gabbro. Sills are most numerous in the oldest part of the succession, the Talga Talga Subgroup.

Massive basalt typically forms darker outcrops than pillow basalt partly because of coarser grain size and less alteration. Alteration visible in the field includes silicification and carbonatization; both features are more pervasive in pillow lavas. Massive basalt is generally jointed at 0.5 to 2 m intervals. A rectilinear to polygonal joint system is developed normal to bedding and another set is oriented parallel to bedding. Vertical joint surfaces are commonly lined with calcite, which also veins the lavas along discontinuous cracks. Columnar jointing is uncommon and poorly developed.

Microscopic examination reveals that the basaltic rocks have been partly to completely recrystallized by greenschist to amphibolite facies metamorphism. Relict clinopyroxene phenocrysts are locally preserved but replacement by amphibole is normally complete. Plagioclase is extensively saussuritized, original labradorite or andesine having been replaced by albite. Lime and alumina released by this process have probably contributed to the formation of secondary amphibole, epidote, clinozoisite and prehnite (Fig. 16). The general mineralogy of the samples thin sectioned is amphibole, (actinolite, tremolite, or hornblende), quartz, (largely secondary), albite, epidote, chlorite and minor sericite, sphene, clinozoisite, carbonate minerals, opaques, prehnite and pumpellyite. Texture ranges from basaltic, in which phenocrysts of pyroxene are set in a fine-grained ophitic to intergranular groundmass of pyroxene, plagioclase and minor quartz, to a crystalloblastic mass of metamorphic minerals; actinolite, in the form of anhedral, almost fibrous aggregates up to 2 mm long, commonly makes up over half the rock. Interstitial material includes fine-grained secondary albite with flakes of amphibole and small porphyroblasts of epidote. Ilmenite is replaced by leucoxene and sphene. Vesicles (Fig. 17) are infilled by chlorite, carbonate, quartz, feldspar and rare apatite.



0·1mm GSWA 19014

Figure 16. Photomicrograph of prehnite within the Honeyeater Basalt, 10 km north of Soanesville. Crossed polars. GSWA 49383.

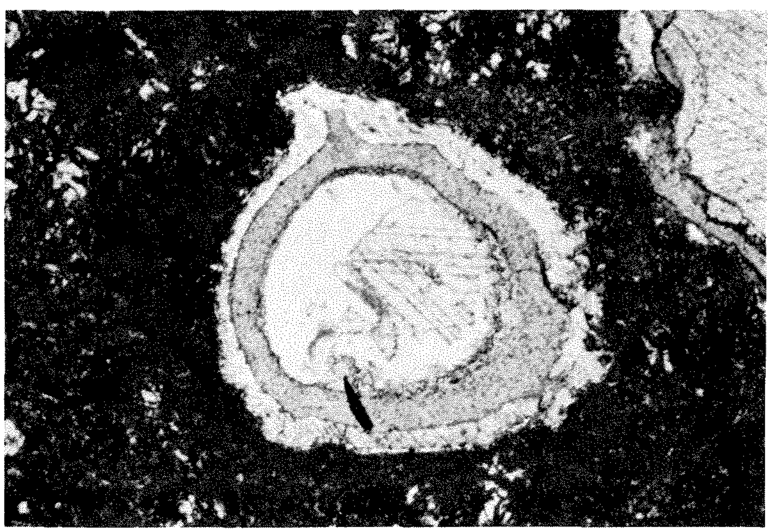


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Figure 17. Photomicrograph of an amygdale in cryptocrystalline basalt 2 km north of Marble Bar Pool. A central area of calcite is rimmed successively by quartz, chlorite and an outer zone of calcite. Plane polarized light. BMR 750 40069C.

AMPHIBOLITE

Tectonic deformation and thermal metamorphism locally transforms basalt and stratiform dolerite into mafic schist or massive, medium-grained, granular, amphibole-plagioclase rock. The rocks vary from green to almost black; plagioclase may be visible in hand specimen but in many samples is difficult to detect due to replacement. The principal outcrops shown on Plate 1A occur north of Farrell Well on the southern margin of the Carlindi Batholith, in the Western Shaw Belt, at Cheearra and in the Roebourne-Karratha-Devil Creek area, but most intrusive granite contacts are bordered by a 1 to 2 km zone of amphibolite-facies metabasalt. Mafic xenoliths within the granitic batholiths are almost invariably composed of amphibolite or of biotite rock after amphibolite. Igneous textures are obliterated and it is usually impossible to determine if the rock was originally basalt or dolerite. Metagabbro locally attains amphibolite facies, but since grain size generally makes its primary composition identifiable it has been shown as gabbro on Plate 1A.

The present mineralogy of amphibolite is largely secondary. In thin section massive amphibolite is a directionless assemblage of variably altered plagioclase (original composition generally labradorite) and pyroxene pseudomorphed by hornblende and/or actinolite (which may ophitically enclose relics of the primary mineral). Glikson (1972a, p. 167), attributed similar replacement in dolerite of the Kalgoorlie area to either late magmatic or metamorphic alteration. During metamorphism alumina released by saussuritization of plagioclase may assist in the conversion of pyroxene to hornblende or secondary actinolite to hornblende. Lime and silica released by uralitization are represented by calcite and quartz, although calcium may be partly taken up in the conversion of ilmenite to sphene (typically cored by exsolved iron oxide). Minor components of the rock include chlorite, phlogopite, rutile and opaques. Fine-grained massive amphibolite (metabasalt or metadolerite) can consist of a mosaic of green hornblende, diopside and altered plagioclase. Large crystals of hornblende contain cores of relict pyroxene. Clinozoisite, granular sphene (after ilmenite), quartz and chlorite are commonly present and scapolite is a rare constituent.

Amphibolite schist is strongly foliated and consists chiefly of felted to granoblastic actinolite or hornblende with subordinate plagioclase, chlorite and epidote, and minor quartz, opaques and carbonate minerals. Some amphibolite schist may represent metamorposed tuff or impure calcareous sediments. Quartz and biotite tend to be more abundant in metatuff.

TREMOLITE-CHLORITE ROCK

The tremolite-chlorite rocks typically show quench-like textures, with intermeshing skeletal or dendritic blades of tremolite as pseudomorphs after pyroxene, or serpentine pseudomorphs after olivine; in many instances this texture is metamorphic rather than primary. The rock has an overall basaltic appearance and composition, but is distinctive by virtue of its unusual texture. The presence of tremolite and olivine results in abnormally high magnesium contents for basalt (i.e. greater than 10 per cent MgO instead of 6 to 8 per cent MgO). Similar rocks elsewhere in the world are commonly referred to as 'high magnesium basalts' or 'basaltic komatiites' (Viljoen and Viljoen, 1969, 1971).

Tremolite-chlorite rocks generally form relatively thin units within piles of tholeiitic basalt, consequently many of the known occurrences cannot be shown on Plate 1A. The rock is mainly encountered within the Apex Basalt, Charteris Basalt, Honeyeater Basalt and the Louden Volcanics at the following localities: Camel Creek, Wyman Well, Blue Bar, Soanesville, Chinaman Creek, Charteris Creek, Sandy Creek, Lionel, Cooke Creek, Farrel Well, Pilbara mining centre (Fitton and others, 1975), Hong Kong mine (Hallberg, 1974) Whim Creek, Mount Negri, Sherlock River, Warambie, Mount Roe, Ruth Well and Mount Regal.

In hand specimen, the tremolite-chlorite rocks vary from pale-grey aphanitic to medium-grained rocks, to dark-grey metabasalt. Crystals from 1 mm to 300 mm in length may produce spinifex texture, but in most rocks the individual laths are about 2-10 mm long. The extrusive origin of the basalt is locally established by pillow structures, but some of the coarser-grained varieties may be high-level intrusives. In the Soanesville area the rock is coarsely dendritic and flow tops are vesicular.

5mm

GSWA 19016

Figure 18A. Spinifex texture in high-magnesium basalt of the Louden Volcanics 15 km south of Sherlock. Skeletal olivine plates (partly replaced by serpentine) are set in a groundmass composed chiefly of secondary amphibole. Plane polarized light. GSWA 49437A.

0·5mm

GSWA 19017

Figure 18B. Above, under greater magnification, showing feathering texture of the groundmass.

Spinifex texture is generally produced by acicular tremolite or, more rarely, chlorite pseudomorphs after clinopyroxene, or serpentine laths after olivine. Clinopyroxene crystals locally possess serpentine cores (probably after olivine) or are rimmed by an inner zone of amphibole and a margin of chlorite. Bladed, skeletal olivine phencrysts may be set in a featherly (plumose) groundmass of pyroxene (altered to tremolite) and plagioclase (including secondary albite) (Fig. 18A, B). Other minerals in the groundmass include epidote, clinozoisite, pumpellyite, carbonate minerals and opaque minerals. Vesicles are filled by calcite, quartz, chlorite or epidote.

It should be noted that not all basaltic rock with a spinifex-like texture is high in magnesium. Metamorphism of basalt or dolerite can produce a similar texture in which hornblende or actinolite laths are set in a feathery groundmass of altered plagioclase. One rock identified in the field as a possible high-magnesium basalt proved to be dolerite containing acicular plagioclase and tremolite (after augite). Hallberg (1974, p. 6) noted a similar problem in the Whim Creek Belt, southeast of Sherlock homestead. Rocks consisting of fresh, euhedral clinopyroxene phenocrysts, plagioclase phenocrysts and calcite-filled amygdales set in a matrix of chlorite, feathery amphibole and minor plagioclase and quartz were found to be of intermediate chemical composition (MgO ranges from 4.01 to 5.23 per cent). Hallberg suggested that this type of rock might result from fractional crystallization of more mafic magma.

Two generations of pyroxene and olivine appear to exist in the tremolite-chlorite rocks. Equant phenocrysts represent early formed crystals, whereas the needles and blades developed by rapid chilling immediately following extrusion. Kjellgren (1976) observed that individual flows near Marble Bar Pool contain a lower porphyritic zone and an upper spinifex zone separated by a central zone containing pyroxene varioles. He interprets this zoning as evidence of a crystal-liquid lava above the liquidus surface, supercooling, and gravitational settling of olivine, clinopyroxene and spinel. Freezing occurred over a small temperature range (cf. Lewis, 1971; Nesbitt, 1971).

ULTRAMAFIC ROCKS

Ultramafic rocks of the Pilbara Block occur in concordant or subconcordant bodies within the layered succession and as sharply discordant dykes and sheets. The concordant units may represent either sills or lava flows, but in most outcrops it is impossible to ascertain which. Features such as spinifex texture and vesicles may be developed in both intrusive and extrusive units, and pillow structures are extremely rare. Many of the discordant intrusions occupy major fault zones related to the main episode of deformation; examples include the periodite-serpentinite unit which extends 70 km from Bamboo Creek to Pear Creek, the peridotite along the southern contact of the Mosquito Creek Synclinorium, and the serpentinite on the southeastern limb of the Indee Syncline.

The ultramafics fall into two principal categories:

(1) those forming thin, laterally extensive, essentially single-rock-type sheets; and
(2) those occurring in relatively thick, layered ultramafic-mafic intrusions.

The first of these groups is chiefly composed of peridotite, serpentinite and altered serpentinite (talc-tremolite-chlorite-carbonate assemblages). In composition, form and general geological setting it closely resembles an alpine-type periodite-serpentinite association.

ULTRAMAFIC ROCKS (NOT SUBDIVIDED)

Outcrops of unsubdivided ultramafic rock shown on Map 1A are composed either of altered rock in which primary composition is indeterminate, or layered ultramafic bodies in which no particular rock type predominates. The larger layered complexes are described separately in the section ULTRAMAFIC-MAFIC INTRUSIONS.

The most common type of altered ultramafic rock is serpentinite which occurs in various forms from massive, granular, apple-green rock (often with ramifying veinlets of chrysotile) to pale green-grey schist. Because serpentinite (generally antigorite) is chiefly a hydrothermal alteration product of olivine, rocks which consist almost entirely of serpentine represent metamorphosed peridotite or dunite; in contrast, pyroxenites are typically replaced by tremolite-talc-chlorite assemblages. Relict textures of cumulus olivine are locally preserved but, in general, rock here referred to as 'serpentinite' is completely recrystallized.

Most serpentinite occurs in stratiform units within basaltic sections of the layered succession. Being relatively susceptible to weathering, the rock rarely forms ridges or hills, but crops out along creeks or gullies and is consequently rather poorly exposed. Examples of serpentinite are numerous but include units at Salgash (15 km southeast of Marble Bar), 5 km south of Eginbah, Kitty Gap, 12 km south of Nullagine, Pilgangoora and Sherlock.

In thin section, massive serpentinite consists of a fine- to medium-grained directionless assemblage of serpentine flakes with minor talc, opaque minerals, chlorite, amphibole, pyroaurite, and carbonate minerals. Iron oxide segregations locally define the margins of altered euhedral olivine crystals (Fig. 21), but elsewhere the opaques adopt a symplectic or dusty habit. Serpentine may also form large poikilitic patches around tremolite (after pyroxene). Foliated serpentinite shows a crude alignment of serpentine flakes or masses of directionless serpentine separated by

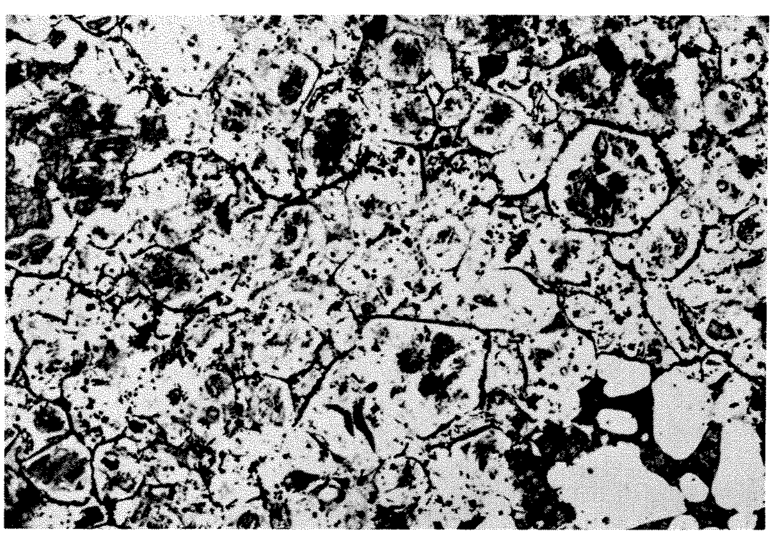

Figure 19. Photomicrograph of olivine cumulus in lherzolite at Stony Creek, 17 km northeast of Lionel. Euhedral olivine crystals (partly serpentinized) are outlined by exsolved iron oxide. Plane polarized light. GSWA 32648.

parallel or braided veins of chlorite, pyroaurite, talc and iron oxide. Some schists include intersecting cleavage planes occupied by these minerals. Two generations of serpentine are common, an early directionless mass, sometimes carbonated, overprinted by later, strongly aligned laths and veins free of carbonate minerals. A late serpentine meshwork may also be restricted to oblique zones, suggesting stress control of recrystallization.

Talc-carbonate rocks crop out as dark brown, poorly foliated to sheared units, generally in association with other ultramafic bodies. Calcite and quartz veins commonly penetrate the rock. As with serpentinite, the rock is widespread although at most localities it forms relatively thin (less than 100 m thick) units. Examples occur 6 km southwest of Eginbah, 9 km southeast of Goldsworthy, at Bamboo mining centre, 8 km south of Soanesville, 6 and 12 km west-southwest of Shaw Gorge, east of Pear Creek, and at Ruth Well. The most easily accessible outcrops are those at Bamboo Creek mining centre.

The development of talc-carbonate rock is controlled by the presence of carbon dioxide during metamorphism and is not directly related to the nature of the original ultramafic rock. Williams (1971), referring to talc-carbonate alteration at Mount Monger near Kalgoorlie, commented that carbon dioxide must be available from an external source such as neighbouring metasediments or volcanics if the process is to reach an advanced stage. Williams also described the progressive alteration of serpentinite to talc-carbonate rock, and stages of the same process appear to have occurred in the Pilbara (i.e. talc occurs in serpentinite, and serpentine in talc-carbonate rock). The origin of the rocks at Bamboo Creek mining centre is probably related to hydrothermal alteration of peridotite, high-magnesium basalt and dolerite, possibly at the time of gold mineralization. Principal minerals are carbonate, talc, quartz and chlorite but relict plagioclase suggests that parts of the sequence were originally dolerite. A thin section of one sample collected from the Bulletin mine shows interstitial glass and acicular pyroxene surrounding euhedral olivine grains up to 1 mm in diameter. This assemblage is bordered by a glassy skin containing small acicular crystals of olivine and pyroxene, clear evidence of rapid chilling on the outer surface of an ultramafic lava or high-level intrusion.

Carbonate-quartz-chlorite rocks crop out 5 km south of Yarrie homestead, in the McPhee Formation at the Talga Talga and Shark mining centres, Nimerry Creek, Bamboo Creek mining centre, south of Blue Bar and at Lynas Find. Many ultramafic units of uncertain composition mapped during recent 1:250 000 scale mapping probably include rocks of this category. The rock crops out as dark brown schist, chlorite being concentrated along the foliation planes. Quartz occurs as grains and veins, some of the latter being auriferous. At Talga Talga and Shark the rock forms high ridges, presumably because of its silica content. The original nature of the rock is indeterminate because textures have generally been completely obliterated, but mineralogical composition suggests that such units include altered pyroxenite, ultramafic tuff, sedimentary carbonate, dolerite or gabbro. Since carbonate minerals and quartz are commonly introduced, their presence need not necessarily reflect the primary composition of the rock; for example, cap rocks over ultramafic bodies commonly possess a similar mineralogy. One such cap rock northeast of Talga Talga possesses a nickel content of 570 ppm and a chromium content of 1 000 ppm, anomalously high for a mafic rock.

In thin section the rock is generally a directionless assemblage of quartz, chlorite and carbonate minerals with minor iron oxide, talc, serpentine, sphene or relict plagioclase.

Tremolite/actinolite-chlorite ± talc rock occurs at numerous localities in the Pilbara Block and probably represents metamorphosed pyroxenite, or, less commonly, high-magnesium basalt. It is developed in similar situations to mafic amphibolite (i.e. near granite-greenstone contacts and in xenoliths), which, except for an absence of plagioclase, it closely resembles. The rock is a massive to schistose, dark grey or grey-green, medium- to coarse-grained meshwork of amphibole laths; chlorite occupies interstitial areas and foliation planes. Although its overall mineralogy is similar to that of high-magnesium basalt, the rock's texture is quite different; it is probable, however, that extensively recrystallized high-magnesium basalt would adopt the metamorphic textue of tremolite/actinolite-chlorite rock. Many of the units are probably metapyroxenite.

PERIDOTITE

Peridotite is the most common ultramafic rock type in the Pilbara Block. Most of it is probably intrusive but this can only be clearly established in the larger bodies and layered complexes. The principal ultramafic complexes are discussed in the section ULTRAMAFIC—MAFIC INTRUSIONS; this section discusses only the relatively thin, stratiform units within the Pilbara Supergroup.

Mineralogically, peridotite is a relatively simple rock consisting principally of olivine with lesser amounts of pyroxene. If both orthopyroxene and clinopyroxene are present, the rock is called a 'lherzolite', if only clinopyroxene accompanies olivine the rock is 'wehrlite', and if the rock consists only of olivine and orthopyroxene the rock is termed 'harzburgite'.

Approximately 50 thin sections of peridotite units have been studied. Serpentinization is ubiquitous, and is so advanced in approximately 50 per cent of the samples that the rocks generally can be identified only as peridotite (with indeterminable pyroxene) rather than dunite (almost entirely olivine). Where pyroxene is preserved, however, it becomes apparent that the most common type of peridotite is phlogopite-lherzolite with a heteradcumulate texture (terminology after Wager and others, 1960). Wehrlite is also quite common and mesocumulate to adcumulate dunite is present at a few localities; harzburgite is comparatively rare. Heteradcumulate peridotite (Fig. 20) consists of serpentinized, euhedral to subhedral olivine cumulus crystals poikilitically enclosed by large pyroxene crystals (partly replaced by amphibole and serpentine). Serpentinized olivine is typically fringed by exsolved iron oxide (Fig. 21). Accessory minerals include biotite and chromite (locally occurring as large pods but generally disseminated) and common secondary products are pargasite, chlorite and tremolite (after pyroxene), hastingsite (after pargasite), talc (after olivine and intercumulus material) and carbonate minerals. Phlogopite is commonly replaced by chlorite, xanthophyllite or clintonite.

Gravitational settling probably accounts for much of the olivine-rich peridotite and such rocks generally grade upwards into pyroxenite, a normal feature of layered intrusions. A peridotite 6 km south of Eginbah homestead shows well developed banding in which layers of olivine cumulate (Fig. 20) about 10 mm thick alternate with thinner layers of opaque minerals exhibiting graded bedding.

Figure 20. Heteradcumulate texture in biotite peridotite 6 km northwest of Spinaway Well. Relatively fresh olivine crystals are enclosed by augite. Plane polarized light. GSWA 32640 .

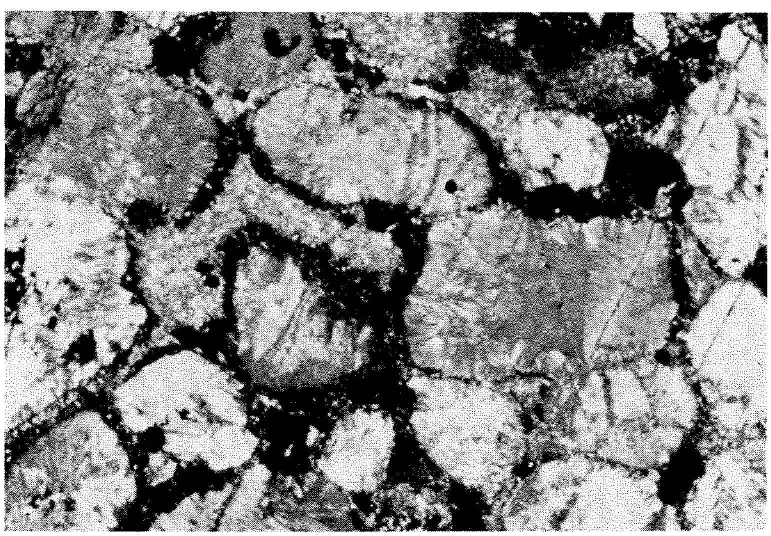

Figure 21. Extensively serpentinized olivine in peridotite 6 km south of Eginbah. Crossed polars. GSWA 4499A.

Drill core obtained by the Utah Development Company (Fitton and Fitton, 1976) 6.5 km west-northwest of Pilbara Well revealed that the lower part of the Euro Basalt (Table 2) is locally composed of 70 individual flows of peridotitic komatiite. The flows range in thickness from 0.4 m to 21.5 m and average 3.7 m. Most consist of a brecciated flow-top underlain by a spinifex-textured zone which is generally fine grained at the top and becomes progressively coarser towards the base. In the thicker flows, this spinifex-textured zone passes down into fine- to medium-grained serpentinized dunite commonly containing thin sub-parallel magnetite stringers which may represent primary flow banding. The base of each flow is generally aphanitic, and some of the lava contains pillow structures. The composition of the flows grades upwards from dunite through peridotite to pyroxene-rich peridotite. Fitton and Fitton (1976) commented that the flows resemble those at Munro Township, Ontario (Pyke and others, 1973). Tomich (1974) has described similar flows at Ruth Well.

PYROXENITE

Pyroxenite has been identified at relatively few localities in the Pilbara Block; these include McPhee Creek, the southern margin of the Yilgalong Granite, Twenty Ounce Gully, Yarrie homestead (3 km south), Eginbah homestead (4 km south), Talga Peak, Farrel Well (7 km north) Soanesville, Dead Bullock Well (7 km east), Pilbara mining centre (7 km west-northwest) Roebourne (5 km south) Ruth Well and Munni Munni Creek.

The rock is typically black to dark grey, medium grained and crops out in low hills or ridges. Microscopic examination shows interlocking pyroxene crystals up to 5 mm in diameter. Minor amounts of plagioclase, olivine hornblende and ilmenite are locally present. According to whether the pyroxene is predominantly clinopyroxene, orthopyroxene or a mixture of both, the rock may be referred to as clinopyroxenite, orthopyroxenite or websterite. McCall (1971, p.440) identifies all three types at Soanesville, although here, as elsewhere, orthopyroxenite is subordinate. Cumulate textures are common, orthopyroxene occurring as scattered phenocrysts or poikilitically enclosing clinopyroxene crystals. Orthopyroxene is variably altered to talc, tremolite or serpentine, whereas clinopyroxene is generally replaced by tremolite and chlorite, and intercumulus plagioclase is saussuritized.

ULTRAMAFIC-MAFIC INTRUSIONS

Ultramafic-mafic layered intrusions and intrusive complexes occur at Munni Munni Creek, Radio Hill, Mount Sholl, Ruth Well, Mount Hall, Mount Langenbeck, Pilgangoora, Strelley Pool, Soanesville and Lionel. The general distribution of these masses (Plate 1A) is not directly related to structure or stratigraphy.

MUNNI MUNNI COMPLEX

Donaldson (1974) described the Munni Munni Complex (48 km southwest of Roebourne) as a layered sequence of clinopyroxenite, peridotite, and gabbro with a total thickness of 5 500 m. Bulk-rock analyses for major and trace elements show similar variation with structural height to that described from the Skaergaard, Bushveld and Stillwater intrusions, although the mineralogical features of the Munni Munni Complex are slightly different.

The intrusion crops out over an area of 80 km^2, the northern half of which is composed of ultramafic rocks. This ultramafic zone is composed of alternating layers of peridotite, clinopyroxenite and porphyritic pyroxenite inclined southeastwards at angles up to 50 degrees. A narrow marginal zone of altered pyroxenite crops out between the complex and neighbouring granitic rocks at its northern and eastern contacts. Boundaries between layers of peridotite (variably serpentinized) and clinopyroxenite are locally gradational with intervening transition units of pyroxene-rich peridotite and olivine pyroxenite. Donaldson (1974) recognized more than 40 cyclic units in the intrusion—peridotite grading upwards into pyroxenite. Fine-scale layering is said to exist in the pyroxenite, olivine-rich bands alternating with pyroxenite at intervals of 2 mm to 200 mm. Gravity stratification is accompanied by pseudo-sedimentary structures such as scour and fill and cross-bedding.

The altered pyroxenite of the marginal zone is composed of altered clinopyroxene (now chiefly fibrous amphibole, chlorite and iron oxide), carbonate, perthite and quartz. Biotite, hornblende, iron-titanium oxides and sulphides are locally prominent. Disseminated and masssive nickel-copper sulphides occur close to the basal contact.

The ultramafic zone contains cumulus crystals of olivine and clinopyroxene with intercumulus orthopyroxene, clinopyroxene and plagioclase. Heteradcumulate textures occur where clinopyroxene poikilitically encloses olivine, but Donaldson (1974, p.5) stated that mesocumulate texture is most common, with monomineralic clinopyroxene adcumulate being less developed.

The upper 3 500 m of the Munni Munni Complex is composed entirely of gabbro. Rhythmic layering is absent but the rock is laminated by virtue of oriented plagioclase laths. Slump structures were noted in a 2 m wide layer, 20 m from the base of the gabbro zone. In thin section the gabbro is seen to be composed of cumulus plagioclase, and intercumulus clinopyroxene and orthopyroxene (inverted pigeonite). Potash feldspar occurs as intercumulate material in the upper part of the gabbro zone. Accessory minerals include ilmenite, biotite, hornblende, magnetite and apatite, and secondary minerals are chlorite, epidote and calcite.

Donaldson concluded that the Munni Munni Complex formed by crystal settling from a melt of tholeiitic composition.

RADIO HILL INTRUSION

Radio Hill is situated at lat. 20° 59′S, long. 116° 50′E, 30 km south of Karratha and 8 km southwest of Mount Sholl. The hill, which rises almost 100 m above the surrounding countryside, is largely composed of gabbro but company drilling and geophysical data have established the presence of underlying peridotite and pyroxenite. Richardson (1976) described the intrusion as a tilted lopolith, some 5 km^2 in area and extending to a depth of 700 m. Country rocks underlying and flanking the lopolith consist chiefly of metabasalt containing minor felsic units. The intrusion is elongated north-south and layering on its margins dips inwards at shallow angles, generally less than 30 degrees. In many respects the geology of the Radio Hill intrusion resembles that of the Munni Munni Complex, situated 12 km to the south. The lower 200 m of the body is composed of alternating layers of peridotite and pyroxenite whereas the central and upper levels of the intrusion are gabbroic, feldspar content increasing upwards until the gabbro grades into diorite and granophyre.

Richardson (1976) noted cumulate texture in the ultramafic rocks similar to those described by Donaldson (1974) in the Munni Munni Complex. The lower levels of the gabbro zone contain cumulus clinopyroxene and orthopyroxene, but cumulate textures are not developed higher in the body. Richardson suggested that the change from cumulate to non-cumulate rocks may be due to an increase in magma viscosity associated with an increase in alumina. Felsic gabbro in the upper part of the intrusion contains large cumulus plagioclase crystals aligned parallel to the general layering.

BULLOCK HIDE WELL COMPLEX

Large outcrops of gabbro, peridotite and pyroxenite occur west of the Dampier-Tom Price Railway 25 km south of Karratha. Extensive Quaternary alluvium between the principal outcrops obscures their mutual relationship and no detailed mapping has been undertaken.

MOUNT SHOLL INTRUSION

The Mount Sholl intrusion is a layered gabbro-norite-pyroxenite-peridotite body cropping out over 30 km^2 of country 9 km south-southeast of Ruth Well. No published information exists, but surface observations and company drilling indicate that the mass is lenticular to funnel shaped and inclined southeastwards at approximately 30 degrees. The upper and lower parts of the intrusion are composed of essentially homogeneous gabbro whereas the core contains alternating layers of peridotite, pyroxenite, norite and gabbro. Gabbro forms the bulk of the Mount Sholl Complex and crops out as low, smoothly undulating hills between Mount Sholl and the road linking Roebourne to Chirratta homestead. Serpentinized feldspathic peridotite is exposed in the northwestern part of the intrusion and a thin, sill-like tongue of gabbro, and peridotite extends 3 km from the northeastern margin. Disseminated pyrrhotite, chalcopyrite and pentlandite occur in the peridotite-gabbro association.

RUTH WELL COMPLEX

Ruth Well is situated 14 km south of Karratha. To the southeast and southwest of the well an igneous complex of metabasalt, gabbro, pyroxenite and serpentinized peridotite and dunite crops out over approximately 10 km^2 of fairly well exposed terrain. Some of the ultramafic bodies are intrusive but company geologists working in the area have noted spinifex-textured flows. Thin layers of peridotite within the pyroxenite indicate that although the complex is folded about east trending axes its general inclination conforms to that of the surrounding Talga Talga Subgroup (Plate 1B); i.e. layers dip between 40 and 70 degrees towards the north.

MOUNT HALL—CARLOW CASTLE COMPLEX

Plate 1A shows a large outcrop of ultramafic rock situated to the southeast and southwest of Roebourne. The mass consists of sheets of dunite, peridotite, pyroxenite, gabbro and minor anorthosite deformed by open folds but generally dipping at about 40 to 60 degrees towards the northwest. No detailed maps of the complex have been published, but field observations have established a general cyclicity conforming to magmatic differentiation trends (i.e. dunite-peridotite-pyroxenite-gabbro-anorthosite in ascending order). Individual cycles are approximately 100 to 200 m in thickness. The total area of the complex is 150 km^2 and its thickness is estimated at 2 km. The complex is intruded by gabbro, dolerite, granitic rocks and pegmatite veins; the latter have been mined for beryl, tantalite and cassiterite. All the ultramafic rocks are serpentinized and chrysotile asbestos has been mined in the Mount Hall area.

SOANESVILLE SILLS

Several differentiated sills intrude the lower part of the Gorge Creek Group on the limbs of the Soanesville Syncline (Hickman and Lipple, 1975, Plate 1). Serpentinization and carbonatization make field identification of primary rock types difficult, but a typical upward sequence is dunite-peridotite-pyroxenite-gabbro-norite and anorthosite (sporadically developed). In most areas, at least some of these rock layers are missing, and simple alterations of peridotite and pyroxenite or peridotite and gabbro are common. The average thickness of a differentiated sill is approximately 400 m, and there are generally between three and five such intrusions on any section into the core of the syncline.

Access to the area is most easily gained from Woodstock via a road leading to the Soanesville asbestos mines. Tracks have been constructed by companies exploring the sill complex for copper-nickel deposits, some of which were located at ultramafic-metasediment contacts. Good examples of differentiation occur 1 km northeast of Soanesville No. 2 mine and around the headwaters of the Turner River 10 km west of Soanesville No. 2 mine. At the Soanesville No. 2 locality cumulate textures are preserved in dunite and hornblende peridotite (probably wehrlite originally). Hornblende rims pyroxene and probably represents a late magmatic replacement; it, in turn, is partly replaced by chlorite. As elsewhere in the Pilbara Block, serpentinization is ubiquitous, but the primary texture of the rocks is outlined by such features as exsolved iron ore, or pentlandite rimming antigorite pseudomorphs.

McCall (1971) presented a cross-section through one of the sill complexes in which chilled pyroxenite grades upwards into dunite, harzburgite, lherzolite, orthopyroxenite, websterite and norite gabbro. Part of the sill is an alteration of gabbro, pyroxenite and chert. McCall considered that the parental magma was highly magnesian, possibly of similar composition to that of the basaltic komatiites of Geluk type.

OTHER LOCALITIES

Peridotite-pyroxenite-gabbro associations occur at numerous other localities in the Pilbara Block, but documentation is limited and it is uncertain how many represent differentiated intrusions. Localities containing the association include Mount Fisher, Whim Creek (5 km west-southwest), Balla Balla, Sherlock Bay (Miller and Smith, 1975; Miller, 1975), Mount Langenbeck (Jones, 1971), Pilgangoora, Abydos (15 km northeast) Strelley mine, Strelley Pool (10 km east-southeast), Blue Bar (12 km south), Lionel, Mosquito Creek mining centre (15 km southeast and 15 km southwest) and McPhee Creek (confluence with Nullagine River). Granophyre is associated with gabbro at Mount Fisher and Sherlock Bay.

Fitton and others (1975, p. 20) grouped most of the occurrences mentioned above together with larger complexes such as those at Munni Munni Creek, Mount Hall and Soanesville, into their newly defined unit, the "Millindinna Complex". They emphasized that this differentiated complex "essentially hugs a regional unconformity between the Upper and Lower Archaean successions". They further claimed that the "Millindinna Complex" occupies an area of 40 000 km^2 which is larger than the extent of any other documented Archaean layered complex.

From the preceding pages (and Plate 1B) it is clear that the various differentiated intrusions of the Pilbara Block occur at many different stratigraphic levels. Thus, although it is possible that the differentiated intrusions may be of the same age (Late Archaean), the concept of a single intrusive sheet occupying one stratigraphic horizon must be rejected.

ROCKS OF MINOR INTRUSIONS

Archaean igneous intrusions, other than granitic plutons and ultramafic bodies described above, take the forms of dykes, sills and stocks of widely varying composition.

FELSIC PORPHYRY

Dacitic plagioclase-phyric porphyry forms dykes, sills and irregular-shaped stock-like masses at numerous localities within the Pilbara Block. The largest stocks occur at Copper Hills and in the Whim Creek—Mount Fraser area, and a thick sill intrudes the Warrawoona Group southeast of Talga Peak.

The Boobina Porphyry (Lipple, 1975) crops out over an area of 50 km^2 between Copper Hills mine and Kelly mine. Euhedral to subhedral phenocrysts of oligoclase (up to 4 mm in diameter), and subordinate quartz are set in dark grey-green, purple or black aphanitic groundmass. The plagioclase phenocrysts locally form glomeroporphyritic groups, and hornblende and biotite are commonly present. Accessory minerals include zircon, iron oxide, apatite and tourmaline, and secondary minerals are chlorite, carbonate, sericite and rutile. Good exposures of the intrusion are available 3 km northwest of Copper Hills on the road to Corunna Downs homestead. The rock crops out in gently undulating country flanked by more rugged terrain—in the northwest the Mondana Adamellite, and to the southeast the Duffer Formation. Intrusive contacts establish that the Boobina Porphyry is younger than the Duffer Formation (ca. 3 450 m.y.) and older than the Mondana Adamellite (probably 2 700-2 600 m.y.). The porphyry exhibits effects of low grade regional metamorphism similar to those in the Duffer Formation. Noldart and Wyatt (1962, p.193) included the intrusion in the Copper Hills Porphyry, but that name is now defunct because the boundaries encompass part of the Duffer Formation.

Between Whim Creek and Mount Fraser, rocks of the Whim Creek Group are intruded by porphyry similar in appearance to the Boobina Porphyry. The plagioclase phenocrysts are euhedral, up to 4 mm in diameter, and range in composition from oligoclase to albite; quartz phenocrysts are generally about 1 mm in diameter. At Mons Cupri, Miller and Gair (1975, p. 198) described a felsic porphyry termed the "Domal rhyolite" which is closely associated with copper mineralization. This rock is said to occupy the necks of volcanoes which were the source of the Mons Cupri Volcanics. Farther southwest, felsic porphyry is too widely distributed (Hickman, 1977d) to be a pipe rock and actually forms irregular-shaped transgressive sills. It is possible that the bodies at Mons Cupri are related to the main porphyry of the Whim Creek Belt, but occur at a slightly higher structural level. The occurrence of spherulitic potash feldspar at Mons Cupri (Miller and Gair, 1975) may indicate more advanced differentiation. Analyses (de Laeter, pers. comm.) suggest, however, that the porphyry at Mons Cupri remains essentially dacitic.

Felsic porphyry similar to that in the Whim Creek Belt, and probably genetically related to it, forms small outcrops 10 km west-southwest of Balla Balla Landing and 8 km northeast of Peawah Hill. A small stock of porphyry also occurs at Toweranna mine where it is host to gold mineralization. Again the rock is dacitic and contains euhedral phenocrysts of quartz, plagioclase (saussuritized) and biotite (altered to chlorite) set in a dark, fine-grained groundmass of quartz and plagioclase.

In the east Pilbara a 1 km-thick sill of felsic porphyry intrudes the contact between the Mount Ada Basalt and the Duffer Formation 10 km east-southeast of Talga Peak. The rock is grey, fine grained and contains abundant euhedral sodic oligoclase phenocrysts (partly sericitized) up to 5 mm in length. The matrix consists of quartz, microcline, plagioclase and green biotite with secondary chlorite and carbonate minerals. Accessory minerals include zircon, iron oxide and apatite.

Small intrusions of plagioclase-phyric dacite occur 9 km northeast of Indee homestead, 5 km northeast of Tambourah, near Kelly mine (dykes intruding the Boobina Porphyry) and 5 km west of Wallabirdee Ridge. North and northeast-trending dykes of porphyritic dacite which intrude the Mount Edgar Batholith 10 km east and southeast of Mount Edgar homestead contain euhedral to subhedral phenocrysts of quartz, microcline and plagioclase set in a fine-grained quartzo-feldspathic groundmass. The age of these dykes is uncertain, but they are tentatively regarded as Archaean. Felsic porphyry stocks of uncertain age intrude the Warrawagine Batholith near Ngarrin Creek. The intrusions occur in an east-northeast trending belt approximately 15 km long. Two distinct rock types are present: a coarse porphyry containing large phenocrysts of quartz and feldspar, and vugs of dark-blue fluorite; and a fine-grained porphyry containing phenocrysts of quartz and perthite in a rhyodacitic matrix (Hickman, 1976).

Sodic porphyry containing abundant aegirine forms a small dyke-like mass in the Muccan Batholith 7 km north of Yarrie homestead. In thin section the rock is crowded with phenocrysts of feldspar and aegirine-augite in a fine-grained matrix of quartz, plagioclase, potash, feldspar and numerous small laths of aegirine. The aegirine-augite phenocrysts are euhedral, from 0.5 to 1 mm across, and are commonly partly altered to epidote, whereas the feldspar phenocrysts are mostly perthite with small lath-shaped inclusions of plagioclase. In some examples a margin of perthite encloses a felted mass of albite laths. A possible explanation for these textures is that metamorphism of primary aegirine-augite could unmix the components to marginal aegirine and diopside which subsequently altered to epidote. If the orginal feldspar phenocrysts were sodic perthite or anorthoclase, metamorphism (or even unmixing during cooling) could cause exsolution of albite.

RHYOLITE AND DACITE

Narrow dykes of rhyolite and dacite intrude the Shaw Batholith between Spear Hill and Shark, greenstones at Nimerry Creek, and the Carlindi Batholith 7 km northeast of Pippingarra mine. the rocks are generally cream or pale pink, fine grained and commonly flow banded parallel to dyke margins. Small phenocrysts of quartz, microcline, perthite, plagioclase and biotite are locally present and the groundmass may contain biotite, muscovite, ferrohastingsite and fluorite. The Archaean age of the intrustions is suggested by the fact that the Shaw Batholith swarm is intruded by the Black Range dyke suite (ca. 2 329 m.y.)

FELSITE

Stratiform sheets of cream to white felsite intrude the Pilbara Supergroup at Wodgina and Stannum. Blockley (1971a) described the rock as fine grained, cleaved, and consisting of small phenocrysts of altered plagioclase and irregular patches of amphibole and chlorite set in a matrix of granulated quartz and feldspar. Fresh microcline is developed in pressure shadows alongside the phenocrysts. The felsite is locally banded and abnormally siliceous, suggesting that metamorphosed felsic tuff may be represented.

PEGMATITE

Pegmatite veins, dykes and pods ranging from a few centimetres in width up to tens of metres are ubiquitous in the granitic complex of the Pilbara Block. Few exposures fail to exhibit pegmatites of some variety and at many localities several phases of pegmatite injection are evident from cross-cutting relationships.

Pegmatite is easily distinguished from whatever type of granitic rock it may intrude, by the relative coarseness of its mineral constituents. The latter are chiefly quartz, potash feldspar, plagioclase and mica, which generally form crystals from about 5 mm up to several metres in diameter. Good examples of the coarser type of pegmatite are exposed at Pippingarra mine where both microcline and muscovite form individual crystals over 1 m across. Another common component of the pegmatite veins is beryl which also forms large crystals or bunches of crystals. At Wodgina, for example, a mass of rosterite (caesium-bearing beryl) associated with albite is reported (Ellis, 1950, p. 35) to have been 11.6 m long, 7.3 m wide and 5.5 m deep before it was mined from the 'Tantalite Lode'. The miners obtained about 750 tonnes of beryl from the deposit.

Most pegmatite veins associated with plutons of the older granitic complex are mineralogically quite simple and devoid of economic minerals such as cassiterite, tantalite, beryl, lepidolite and radioactive compounds. Pegmatites associated with the post-tectonic granitic plutons, however, commonly do contain these minerals, and Blockley (1970, 1971a, and 1980) has studied these late Archaean intrusions in considerable detail. A result of this work has been the recognition of three types of tin-bearing pegmatite: simple pegmatite; layered albite pegmatite; and complex rare-metal pegmatite. Simple pegmatite is generally composed of quartz, albite and muscovite with lesser amounts of cassiterite, tantalite-columbite minerals and rarer lithium and beryllium compounds. Layered albite pegmatite veins are composed of bands of fine-grained quartz-albite aplite alternating with coarser quartz-microcline-albite-muscovite pegmatite. Cassiterite, tantalite and columbite, lepidolite, zinnwaldite, beryl, gadolinite and monazite are accessory economic minerals. Other minerals occurring in non-commercial amounts include spessartine, tourmaline, magnetite, topaz, zircon, fluorite, simpsonite and wodginite. Most cassiterite in the layered pegmatite veins is concentrated in the finer albitic phase (commonly at or near vein margins) which probably formed by soda metasomatism of microcline. Good exposures of layered pegmatite are present on MC 892 at Moolyella, in the headwaters of Mulgandinnah Creek, at Shaw Patch, east of Spear Hill, near the old plant at Cooglegong and at the head of Old Shaw Creek. In complex rare-metal pegmatite, cassiterite is commonly subordinate to tantalite, columbite, beryl and lithium minerals. Most rare-metal pegmatites intrude greenstones rather than granitic rocks, although exceptions to this generalization do occur at Numbana.

Not all tin-bearing pegmatite bodies are unambiguously associated with the post-tectonic intrusions. As noted above, such a pegmatite at Wodgina has been dated at 2 930 m.y. (Greenhalgh and Jeffery, 1959) suggesting a genetic relationship to the older complex. Similar pegmatite bodies also occur at Pilgangoora and Mount Hall where no associated post-tectonic intrusions have been identified.

MICROGRANITE

Two northerly-trending dykes of microgranite are intruded by the Black Range dyke 10 km south-southwest of Coondina. The dykes are approximately 15 m wide and composed of massive, pink, granophyric microgranite. The rock is leucocratic and contains rare phenocrysts of microcline. A similar dyke occurs north of Corunna Downs homestead.

DIORITE

Diorite sills intrude the Archaean layered succession 15 km northeast of Woodstock and 15 km east-northeast of Abydos. The rock contains approximately equal amounts of plagioclase and hornblende with minor quartz. It crops out in massive, well-jointed lensoid bodies and may be related to differentiated gabbroic sills and granophyric diorite in the Soanesville Syncline.

GABBRO

Archaean gabbro sills intrude the Pilbara Supergroup in many areas of the block. Most of these bodies are simple intrusions and show no features of differentiation. Typical examples of thick gabbro sills occur at Station Peak, south of the Satirist Batholith, Talga Peak (10 km east), Strelley Pool (8 km south-southwest), Wallabirdee Ridge (2 km west and 7 km southeast), Charteris Creek, and in the Mosquito Creek Formation near Cooke Creek mine and at Coondamar Creek. Other sills, too thin to represent even on a 1:250 000 scale map, are common in the Talga Talga Subgroup.

Despite alteration such as saussuritization and carbonatization, original textures are generally well preserved. Euhedral phenocrysts of orthopyroxene originally set in a micrographic intergrowth of plagioclase and clinopyroxene are variably altered to serpentine pseudomorphs surrounded by tremolite, chlorite, carbonate, quartz, epidote, sericite, clinozoisite and opaques. Hornblende may replace pyroxene, and ilmenite is generally altered to granular sphene. Hypersthene is generally present in the Archaean gabbro intrusions, but norite is relatively uncommon. No alkali gabbro has been observed and olivine is absent. The sills are chemically very similar to the tholeiitic basalt units which they intrude.

DOLERITE

The distribution and form of dolerite intrusions is similar to those of gabbro. Where dolerite occurs as sills in basaltic units of the layered succession it is commonly difficult to determine whether or not it is of intrusive or extrusive origin. In fact the distinction, where it can be made, is probably of rather academic interest since, as with gabbro, most of the dolerite is almost certainly comagmatic and broadly coeval with the basalt.

Archaean dolerite dykes which intrude the area's granitic batholiths can be distinguished from Proterozoic intrusions because they are normally foliated, metamorphosed to amphibolite facies, and follow sinuous courses. Examples of such dykes occur close to the southern margin of the Mount Edgar Batholith, near Abydos, Callawa, and south of Yandeearra homestead. Sharply discordant Archaean dolerite dykes intrude the Warrawoona Group between Marble Bar and Doolena Gap. Many of these intrusions occupy a fracture system diverging from the northwestern contact of the Mount Edgar Batholith. Large dykes also penetrate the layered succession at Warrery Gap (5 km west).

Alteration of the dolerite is similar to that in gabbro, but generally less advanced than that in adjacent basalt. Hypersthene is a common constituent.

T-CHERT

T-chert (tectonically controlled chert, Dunbar and Rodgers, 1961) is distinguished from normal sedimentary chert by its lack of internal banding and its discordant relations to adjacent strata (Fig. 22). The existence of T-chert in the Pilbara was first reported at North Pole (Hickman, 1973) where the rock has intruded the fracture system of a dome, producing a boxwork pattern of dykes. The origin of the T-chert at North Pole remains a subject of some speculation. It was originally considered that the chert was fumarolic and the intrusions represented feeders to

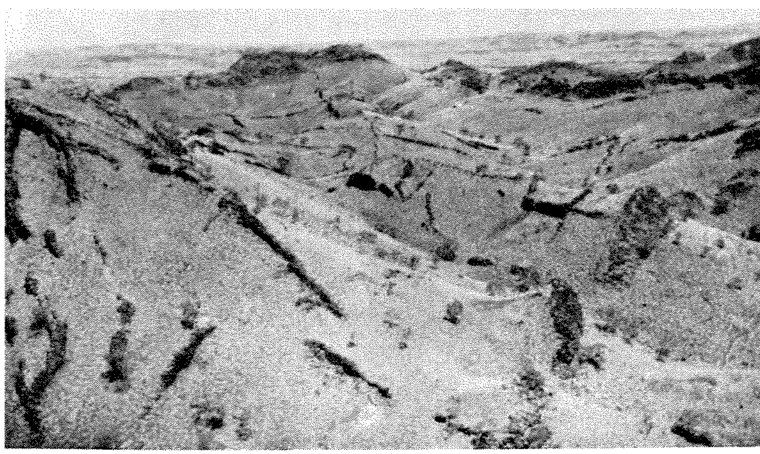

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Figure 22. Boxwork pattern of T-chert dykes at North Pole.

bedded sedimentary chert units of the Towers Formation. Two observations militate against this interpretation: (1) the intrusive chert is injected along fault planes which displace the sedimentary chert units; and (2) the T-chert penetrates the layered succession above the level of the highest sedimentary chert. Moreover even fumarolic chert veins might be expected to show some degree of internal banding due to crustification against their wall rocks. A minority of the discordant chert units may be fumarolic but most would appear to have formed in response to stress during doming. Solution and mass migration of sedimentary chert under conditons of greenschist facies metamorphism is difficult to envisage and it may be that the sedimentary chert was still relatively plastic at the time of deformation, perhaps due to connate water having been trapped beneath the overlying basaltic pile. Sedimentary barite at North Pole and unusual textures in parts of the sedimentary chert could indicate that the chert is a secondary replacement of carbonate or evaporite deposits. Although this interpretation is not firmly accepted, it is easy to evisage mobilization of limestone under quite low stress conditions, and such a process must be considered as one possible explanation of the T-chert.

Other T-chert complexes occur between Sandy Creek and Spinaway Creek, 10 km southeast of Yandicoogina, Police Creek, and along a major fault zone 10 km southeast of Cooke Creek mine. At the locality southeast of Yandicoogina the rock intrudes sandstone, and a local derivation by solution of silica is indicated.

QUARTZ

Essentially monomineralic quartz veins are widespread in the granitic complex and in the more attenuated regions of the Pilbara Supergroup. In the latter, the veins are commonly mineralized by gold and copper minerals, and more rarely by antimony, lead, tungsten, zinc and molybdenum. Quartz veins in the greenstones are concentrated close to the granite contacts, and generally occupy strike faults. In the granitic complex the quartz is typically barren and intrudes major fractures up to 50 km in length (e.g. between Wodgina and Tabba Tabba mine).

STRATIGRAPHY

INTRODUCTION

Present geochronological information indicates that the Archaean stratigraphic succession of the Pilbara Block was deposited over a period of approximately 900 m.y. (i.e. from about 3 500-2 600 m.y. ago). The maximum total thickness of the succession ranges up to 25 or 30 km (Table 2), and it is important to note that prior to deformation the Warrawoona Group and the lower part of the Gorge Creek Group (excluding the Mosquito Creek Formation) were essentially tabular units across the greater part of the craton. The maximum true thickness preserved in any single area is about 15 km. Until recently it was generally believed that Archaean depositional basins occupied zones of crustal weakness which were subject to downwarping, magmatic intrusion and volcanism. The margins of such basins, or troughs, were thought to broadly correspond to those of the present greenstone belts, but this is not the situation in the Pilbara Block. There is no evidence of stratigraphic thinning or facies changes from the centres of the belts towards their margins; where attenuation does occur, deformed pillows and clasts, and the development of schistosity establish that it is chiefly tectonic. Moreover, at North Pole and McPhee Creek, the succession continues unmodified across greenstone domes 30 to 40 km in diameter. A granitic core is exposed in the centre of North Pole Dome, and Bouguer anomaly patterns suggest that the McPhee Dome is also underlain by granitic rocks.

In view of the thickness of the succession and the great time span involved it is perhaps surprising that the Pilbara Supergroup contains only three groups and a total of 20 formations (Table 2). Assuming that Archaean lava flows and sediments accumulated at comparable rates to similar Phanerozoic deposits, at least one of the unconformities in the succession must represent a major hiatus. The most important unconformity is probably that between the Gorge Creek Group and the Whim Creek Group.

PREVIOUS INTERPRETATIONS

Previous stratigraphic subdivisions of the Archaean layered succession are noted in Chapter 1. Maitland (1906) established that the stratigraphy of the Pilbara Block consisted of the "Warrawoona Beds" (now the Warrawoona Group) overlain by the "Mosquito Creek Series" (now the Gorge Creek Group) unconformably overlain by the "Nullagine Beds" (Proterozoic). The relative ages of the "Warrawoona Beds" and the "Mosquito Creek Series" remained uncertain for some time (e.g. Woodward, 1911)

TABLE 2. PRECAMBRIAN STRATIGRAPHIC COLUMN OF THE PILBARA BLOCK AND ITS ENVIRONS

Age	Super-group	Group	Sub-group	Formation	Lithology	General thickness (km)
?——MIDDLE PROTEROZOIC				Eel Creek Formation	Shale sandstone and iron-formation	0.5
					RELATIONS UNCERTAIN	
			MANGANESE SUBGROUP		Shale and sandstone	0.5
					UNCONFORMITY	
		YENEENA GROUP			Sandstone, shale and Carbonate rocks	>5.0
					? DISCONFORMITY	
				Waltha Woora Formation	Shale, siltstone and dolomite	0.1
					UNCONFORMITY	
				Pinjian Chert Breccia	Silicified Chert breccia	<0.1
					UNCONFORMITY	
EARLY PROTEROZOIC	MOUNT BRUCE SUPERGROUP	HAMERSLEY GROUP		Weeli Wolli Formation	Shale, iron formation and dolerite	0.5
				Brockman Iron Formation	Banded iron-formation	0.6
				Mount McRae Shale	Shale	0.1
				Mount Sylvia Formation	Shale and minor iron formation	<0.1
				Carawine Dolomite	Dolomite and minor chert	0.2
				Marra Mamba Iron Formation	Jaspilite and chert	0.2
		FORTESCUE GROUP		Jeerinah Formation	Shale, sandstone and chert	0.3
				Maddina Basalt	Basalt	0.2
				Kuruna Siltstone	Siltstone	0.1
				Nymerina Basalt	Basalt	0.3
				Tumbiana Formation	Carbonate rock and tuff	<0.1
				Kylena Basalt	Basalt and local sandstone	0.3
				Hardey Sandstone	Sandstone, conglomerate and shale	1.0
				Mount Roe Basalt	Basalt and local agglomerate	0.2
					UNCONFORMITY	
				Negri Volcanics	Variolitic basalt and andesite	0.2
					UNCONFORMITY	
				Louden Volcanics	Basaltic and ultramafic rocks	1.0

TABLE 2—continued

Age	Super-group	Group	Sub-group	Formation	Lithology	General thickness (km)
ARCHAEAN	PILBARA SUPERGROUP	WHIM CREEK GROUP		Rushall Slate	UNCONFORMITY Slate, minor andesite and tuff	0.2
ARCHAEAN	PILBARA SUPERGROUP	WHIM CREEK GROUP		Mons Cupri Volcanics	Felsic volcanics	0.5
ARCHAEAN	PILBARA SUPERGROUP	WHIM CREEK GROUP		Warambie Basalt	Basalt	0.2
ARCHAEAN	PILBARA SUPERGROUP	GORGF CREEK GROUP		Mosquito Creek Formation	UNCONFORMITY Psammitic to pelitic schist	5.0
ARCHAEAN	PILBARA SUPERGROUP	GORGF CREEK GROUP		Lalla Rookh Sandstone	Sandstone and conglomerate	3.0
ARCHAEAN	PILBARA SUPERGROUP	GORGF CREEK GROUP		Honeyeater Basalt	LOCAL UNCONFORMITY Pillow basalt	1.0
ARCHAEAN	PILBARA SUPERGROUP	GORGF CREEK GROUP	SOANESVILLE SUBGROUP	Cleaverville Formation	Banded iron-formation	1.00
ARCHAEAN	PILBARA SUPERGROUP	GORGF CREEK GROUP	SOANESVILLE SUBGROUP	Charteris Basalt	Basalt and dolerite	1.0
ARCHAEAN	PILBARA SUPERGROUP	GORGF CREEK GROUP	SOANESVILLE SUBGROUP	Corboy Formation	Sedimentary rocks	1.5
ARCHAEAN	PILBARA SUPERGROUP	WARRAWOONA GROUP		Wyman Formation	LOCAL UNCONFORMITY Porphyritic rhyolite and local tuff	1.0
ARCHAEAN	PILBARA SUPERGROUP	WARRAWOONA GROUP	SALGASH SUBGROUP	Euro Basalt	LOCAL UNCONFORMITY Basalt and dolerite	2.0
ARCHAEAN	PILBARA SUPERGROUP	WARRAWOONA GROUP	SALGASH SUBGROUP	Panorama Formation	Felsic volcanics and sediments	1.0
ARCHAEAN	PILBARA SUPERGROUP	WARRAWOONA GROUP	SALGASH SUBGROUP	Apex Basalt	Basalt and high-Mg basalt	2.0
ARCHAEAN	PILBARA SUPERGROUP	WARRAWOONA GROUP	SALGASH SUBGROUP	Towers Formation	? LOCAL UNCONFORMITY Chert and basalt	0.5
ARCHAEAN	PILBARA SUPERGROUP	WARRAWOONA GROUP		Duffer Formation	Felsic volcanics	5.0
ARCHAEAN	PILBARA SUPERGROUP	WARRAWOONA GROUP	TALGA TALGA SUBGROUP	Mount Ada Basalt	LOCAL UNCONFORMITY Basalt	2.0
ARCHAEAN	PILBARA SUPERGROUP	WARRAWOONA GROUP	TALGA TALGA SUBGROUP	McPhee Formation	Carbonate-chlorite-quartz rock	0.1
ARCHAEAN	PILBARA SUPERGROUP	WARRAWOONA GROUP	TALGA TALGA SUBGROUP	North Star Basalt	Basalt and dolerite	2.0

but Maitland (1919) reported a conglomerate in the "Mosquito Creek Series" which he said contained pebbles of the "Warrawoona Beds". Finucane (1939b) substantiated Maitland's interpretation by mapping an unconformity between the two units at Eastern Creek. Noldart and Wyatt's (1962) subdivision of the "Mosquito Creek succession" was lithological rather than stratigraphic and Ryan's (1964, 1965) "Roebourne Group" in the West Pilbara remained a tenable stratigraphic unit for a relatively short period of time only, (Fitton and others, 1975). It should be noted, however, that Ryan and Kriewaldt (1963) correctly subdivided part of the west Pilbara succession into four stratigraphic units: (1) amphibolite, ultrabasic rocks and acid lava (now the Talga Talga Subgroup and Duffer Formation); (2) chert and clastic sedimentary rocks (now the Towers Formation); (3) basic volcanic rocks (now the Salgash Subgroup); and (4) banded iron-formation (now the Cleaverville Formation).

A preliminary version of the present stratigraphic subdivision was circulated during a Geological Survey of Western Australia field excursion in 1974. One participant of the excursion, Mr M. J. Fitton, informed the writer that the Marble Bar succession established by the Geological Survey was virtually identical to that at the Pilbara mining centre 150 km to the west: both successions were published in the following year (Hickman and Lipple, 1975; Fitton and others, 1975).

Ingram (1977) subdivided the Warrawoona Group into four formations (including the "Gorge Creek Formation"), none of which contains any predominant rock type; instead, each of the formations is composed of genetically related rock units (e.g. the two central formations are essentially mafic-felsic volcanic cycles).

METHOD OF SUBDIVISION AND CORRELATION

The Archaean layered succession of the Pilbara Block is now subdivided according to the Australian Code of Stratigraphic Nomenclature (Geological Society of Australia, 1964, revised, 1973). Hierarchial terms applied to rock stratigraphic units under the Code are, in ascending order: member, formation, subgroup, group and supergroup. The primary unit is the formation which is a mappable unit consisting either of one dominant lithology or of two or more associated lithological types. It is important that adjacent formations should be separated by a clearly defined contact. Unless the latter is a stratigraphic break (unconformity or disconformity), the adjacent formations should be lithologically distinctive. Except for the Towers Formation, each of the twenty formations which make up the Pilbara Supergroup is composed of a particular dominant lithology.

The present subdivision originated in 1972 during the Geological Survey's remapping of the Marble Bar 1:250 000 Sheet (Hickman and Lipple, 1975). Subsequent mapping in other areas (Hickman, 1975a; Fitton and others, 1975; Hickman, 1977a, d) led to amplification of the initial stratigraphic column, a process which depended on correlations between the greenstone belts. Stratigraphic correlation between greenstones belts has rarely been attempted in other shield areas of the world, partly because of poor exposure but also due to the fact that individual greenstone belts have commonly been regarded as separate depositional basins. Stratigraphic correlation in the Pilbara Block is facilitated by good exposure and a partial continuity between greenstone belts. Where individual belts are separated by granitic rocks or Proterozoic cover, correlations are based on marker units (especially the Towers Formation) and/or similarity of lithological sequence. The confidence with which similar sequences can be correlated is enhanced by the general absence of rapid lateral facies changes in the volcanics. This point is illustrated by stratigraphic columns through the Warrawoona Group near Dampier, Roebourne, Marble Bar and McPhee Creek (Plate 2). Thick sedimentary units are confined to the Gorge Creek Group.

PILBARA SUPERGROUP

The Archaean layered succession of the Pilbara Block is now referred to as the Pilbara Supergroup. This name replaces "Pilbara System" (Noldart and Wyatt, 1962, p. 100), the term "system" no longer being permissible under the Australian Code of Stratigraphic Nomenclature. Ryan (1964, 1965) redefined "Pilbara System" to include the area's granitic rocks, a practice which should now be discontinued.

The Pilbara Supergroup derives its name from the Pilbara mining centre, the scene of the first major gold discovery in the northwest of Western Australia. The Pilbara Goldfield was created in 1888, and subsequently the entire northwestern part of the State has become known as the Pilbara region. The Pilbara Supergroup includes a wide range of volcanic rock types, consanguineous high-level sills (chiefly dolerite), and sedimentary rocks; it is composed of three groups and two formations:

Top	Negri Volcanics
	Louden Volcanics
	Whim Creek Group
	Gorge Creek Group
Bottom	Warrawoona Group

The true thickness of the supergroup (not complete in any single area) ranges from 20 to 30 km, and it crops out over an area of 24 000 km^2. The Warrawoona Group is intruded by Archaean granitic rocks ranging in age up to 3417 $\pm$ 40 m.y. (Pidgeon, 1978b). Rocks in the central part of the Warrawoona Group have been dated at 3 500 m.y. (Sangster and Brook, 1977), 3 453 m.y. (Pidgeon, 1978) and 3 340 m.y. (Richards, 1978). Close to the top of the succession the Whim Creek Group unconformably overlies Archaean Granite dated at 2 700 m.y. (de Laeter, pers. comm.), and is intruded by rocks ranging in age from 2 500 m.y. to 2 330 m.y. (de Laeter, pers. comm.). All stratified units except the Negri Volcanics are unconformably overlain by Lower Proterozoic rocks of the Fortescue Group, now considered to be as old as 2 650 – 2600 m.y. (Hickman and de Laeter, 1977).

WARRAWOONA GROUP

The Warrawoona Group contains nine formations and is composed chiefly of volcanic rocks. The present subdivision of the group, which was first published by Hickman (1977c), is similar to that previously presented by Hickman and Lipple (1975) and Lipple (1975), but formally names six formations not previously defined. Other stratigraphic subdivisions of the succession presented by Fitton and others (1975) and Ingram (1977) are noted in Table 3.

The Warrawoona Group derives its name from Warrawoona mining centre where Maitland (1905) first used the name "Warrawoona Beds" to describe a sequence of greenstones. The stratigraphic base of the group has not been observed (this point is discussed later) and its lower contact with neighbouring granitic rocks is locally

TABLE 3. STRATIGRAPHIC SUBDIVISION OF THE WARRAWOONA GROUP

<table>
<tr><th rowspan="2">Formation</th><th rowspan="2">Thickness (km)</th><th rowspan="2">Lithology</th><th colspan="2">Previous Subdivisions</th></tr>
<tr><th>Fitton and others (1975), West Pilbara</th><th>Ingram (1977), East Pilbara</th></tr>
<tr><td>Wyman Formation</td><td>0-1.0</td><td>Porphyritic, columnar-jointed rhyolite. Local tuff, agglomerate and basalt</td><td>Wyman Formation</td><td rowspan="4">Miralga Formation</td></tr>
<tr><td>Euro Basalt</td><td>2.0</td><td>Pillow basalt with minor chert and felsic volcanic units. Local peridotitic komatiite near base.</td><td rowspan="3">Empress Formation</td></tr>
<tr><td>Panorama Formation</td><td>0-1.0</td><td>Dacitic lava, tuff and agglomerate, and chert. Local sandstone, conglomerate and ultramafic rocks.</td></tr>
<tr><td>Apex Basalt</td><td>1.5-2.0</td><td>Pillow basalt and high-magnesium basalt. Numerous chert units and minor dolerite and gabbro sills.</td></tr>
<tr><td>Towers Formation</td><td>0.5</td><td>Three chert members separated by basalt, komatiite, felsic volcanics or sediments. Includes the Marble Bar Chert Member (100 m thick).</td><td>Hong Kong Chert</td><td rowspan="3">Sharks Formation</td></tr>
<tr><td>Duffer Formation</td><td>0-8.0</td><td>Dacitic tuff, agglomerate and lava. Minor chert, shale and basalt. Local porphyritic intrusions.</td><td rowspan="4">Friendly Creek Formation</td></tr>
<tr><td>Mount Ada Basalt</td><td>2.0-2.5</td><td>Pillow basalt, massive basalt, and minor chert, dolerite and gabbro. Local chert, black shale and felsic tuff.</td></tr>
<tr><td>McPhee Formation</td><td>0.05-0.20</td><td>Carbonate-quartz ± chlorite schist. Subordinate chert. BIF, pelite and tuff. May include carbonate sediments.</td><td rowspan="2">Chocolate Hill Formation</td></tr>
<tr><td>North Star Basalt</td><td>2.0</td><td>Massive basalt and pillow basalt with numerous sills of dolerite and gabbro. Minor chert, serpentinite and felsic lava.</td></tr>
</table>

tectonic and elsewhere intrusive. The top of the Warrawoona Group is defined by its boundary with the Gorge Creek Group. Local unconformities occur at this stratigraphic position in many parts of the Pilbara Block, but in most places the two groups appear to be broadly conformable.

The Talga Talga Subgroup and the Salgash Subgroup (defined by Lipple, 1975) are two major basaltic divisions which together make up much of the Warrawoona Group (Table 2). Mapping in the northern and western parts of the Pilbara Block during the period 1974-1976 resulted in the subdivision of both these subgroups into formations. Consequently, the usefulness of the two names has diminished, and they are now restricted to areas where boundaries between the component formations have yet to be established (e.g. in the Salgash Subgroup between Roebourne and Nickol River).

North Star Basalt

The oldest formation of the Warrawoona Group, the North Star Basalt (Hickman, 1977c), is exposed over 50 km^2 south and east of Talga Talga mining centre. The type section follows the road between the Great Northern Highway and McPhee Reward mine. The North Star Basalt has also been mapped on the Western side of the Coongan Belt mining centre. In the west Pilbara, the McPhee Formation, which separates the formation from the lithologically similar Mount Ada Basalt, is recognized only south of Whundo, and the North Star Basalt is not distinguished from the remainder of the Talga Talga Subgroup (Plate 1B). The latter also remains unsubdivided in parts of the east Pilbara, pending more detailed mapping.

The North Star Basalt derives its name from North Star mine. Massive basalt, pillow basalt and numerous sills of dolerite and gabbro make up the bulk of the formation. At McPhee Reward mine and Shark mining centre a thin felsic lava member at the top of the unit is overlain by clastic sediments, chert and tuff of the McPhee Formation. Rare chert and serpentinite units are locally developed in the centre of the North Star Basalt, and the unit's general thickness is about 2 000 m. Several stratigraphic sections through the formation are included in Plate 2.

The North Star Basalt is metamorphosed to greenschist and lower amphibolite facies. Metabasalt now consists of clumps of green amphibole (actinolite to hornblende) set in a finer grained mass of albite with lesser amounts of chlorite, epidote, clinozoisite, quartz, opaques, sphene and carbonate minerals. The clumps of green amphibole (in various stages of alteration to chlorite) are commonly radiating. In general the rock exhibits no original igneous textures, but some fine-grained varieties do retain their basaltic texture. Relict vesicles are locally present and are infilled with quartz, feldspar, chlorite and rare amphibole.

McPhee Formation

The McPhee Formation (Hickman, 1977c) derived its name from McPhee Reward mine at the Talga Talga mining centre, 20 km north-northeast of Marble Bar. The type section is exposed in a gorge 100 m southwest from the mine, and the formation crops out between Nimerry Creek and a point 2 km northeast of Pyramid Well. Other areas in which the McPhee Formation has been mapped are on the western limb of the Coongan Syncline (30 km southwest of Marble Bar) and in the Whundo area (Plate 1B).

Rock types exposed in the type section are summarized below:

	Thickness (m)
Mount Ada Basalt (base)	
Pillow basalt	
* * * *	
McPhee Formation	
Carbonate-chlorite-quartz rock	10
Banded ferruginous chert	1
Carbonate-chlorite-quartz rock	15
Chert	0.1
Carbonate-chlorite-quartz rock	2
Ferruginous chert	1
Carbonate-chlorite-quartz rock	3
Ferruginous chert	0.5
Pyritic basalt (altered)	1
Carbonate-chlorite-quartz rock	2
Pyritic ferruginous chert	1
Carbonate-chlorite-quartz rock	1.5
Brecciated ferruginous chert	0.5
Carbonate-chlorite-quartz rock	5
Basalt (altered)	8
Ferruginous chert	2
Grey/white banded chert (drill core reveals some pelite and marl)	25
* * * *	
North Star Basalt (top member)	
Porphyritic dacite and andesite	

The primary mineralogy of the carbonate-chlorite-quartz rock, which comprises the bulk of the formation, cannot be determined in thin section. Schistosity, or layering, is a prominent feature of the rock both in the field and under microscopic examination, and it is probably significant that this foliation is confined to the ultramafic unit, and parallel to bedding in the adjacent chert and basalt units. Moreover, the ultramafic unit is obviously not a single intrusion since it contains several laterally continous chert units. Company geologists working in the area have reported possible pillow structures suggesting that the formation includes lava. Nickel and chromium contents are far too high (approximately 1 000 ppm Ni, 2 000 ppm Cr) for the schist to be an altered tholeiitic basalt. All these features indicate that the rock was originally an ultramafic lava and/or tuff unit perhaps of komatiitic type.

In the Coongan Syncline the McPhee Formation crops out along a strike length of 13 km at Shark mining centre and 23 km near Coongan Belt mining centre (5 km west). At Shark it is composed of carbonate-chlorite-quartz rock similar to that at McPhee Reward mine, but at Coongan Belt it is chiefly composed of ultramafic amphibolite; both outcrops are underlain by thin units of felsic schist representing the top of the North Star Basalt. Rocks correlated with the McPhee Formation south of Whundo consist of ultramafics and chert.

Mount Ada Basalt

At Talga Talga, Shark, Coongan Belt and Whundo mining centres, the McPhee Formation is comfortably overlain by a 2 000 to 2 500 m thick succession of pillow and massive basalt flows, dolerite sills and minor thin chert units, collectively named the Mount Ada Basalt (Hickman, 1977 c). Basalt is estimated to comprise about 80 % of the formation. A good section through the unit is available on a track leading from Mount Ada mine northwards to the base of the Duffer Formation, 1.5 km west of Glen Herring Creek; but the type section is designated as a traverse line extending 3km northwestwards from McPhee Reward mine to the base of the Duffer Formation, 5 km east of the Coongan River.

The Mount Ada Basalt crops out over an area of 100 km^2 northeast and southwest of McPhee Reward mine, over 50 km^2 north and south of Mount Ada mine, and over 50 km^2 west of Coongan Belt. The formation is also present at McPhee Creek, near Whundo, and at numerous localities where the Talga Talga Subgroup is not subdivided (Plate 1B).

In the Talga Talga area the Mount Ada Basalt differs from the North Star Basalt in being extensively carbonatized; its average CO_2 content, as determined from 20 samples, is about 5 per cent. This difference is quite pronounced; no sample from the North Star Basalt (excluding one collected immediately beneath the McPhee Formation) has more than 1.1 per cent CO_2 whereas all samples of the Mount Ada Basalt at this locality contain more than 1.1 per cent CO_2. The reason for this discrepancy remains uncertain. High CO_2 contents are not a regional feature of the Mount Ada Basalt (e.g. samples from the Mount Ada section average 0.95 per cent CO_2). A thin (approx. 5 m), but laterally persistent, felsic tuff unit is present 300 m from the base of the formation northwest of McPhee Reward mine, and rare ultramafic intercalations occur near the top of the section. Immediately beneath the Duffer Formation, chert, BIF and siltstone form the top of the Mount Ada Basalt but these members wedge out southwestwards suggesting the existence of a low-angle unconformity at the top of the formation.

The Mount Ada section contains two central bands of pelite, ferruginous chert and felsic tuff, but sediments are not present at the top of the formation.

Samples of metabasalt and metadolerite from the McPhee Reward and Mount Ada sections have undergone retrograde metamorphism to the greenschist facies. Equilibration in the greenschist facies has not always been reached, however, and relict pyroxene altering to actinolite and chlorite is locally observed. The ferromagnesian minerals are set in a matrix of albite laths, amphibole and chlorite. Despite carbonatization at McPhee Reward mine, rocks of both sections contain fairly well preserved relict igneous textures. Minor minerals are typically secondary quartz, epidote, opaques and sphene.

Duffer Formation

The Duffer Formation (Hickman and Lipple, 1975; Lipple, 1975) is composed of dacitic lava, tuff and agglomerate, with subordinate rhyolite, basalt, chert and porphyritic intrusions. Easily accessible exposures of the unit are available at Duffer Creek 10 km north of Marble Bar, and in the area between Marble Bar and the Coongan River; but the type section is herein designated as the creek running from Bowls Gorge (local name) to the Coongan River, 14 km north of Marble Bar. Hickman and Lipple (1975) showed a large part of this section to be composed of basaltic rocks, but a detailed traverse conducted for the purpose of geochemical sampling has since established that basalt forms only a minor part of the succession.

The distribution of the Duffer Formation is shown on Plate 1B. The largest outcrop occupies an area of 400 km^2 extending from Salgash mining centre northwards through Marble Bar to a point 8 km southwest of Coppin Gap. Other extensive outcrops occur at McPhee Creek, Copper Hills, Glen Herring, and in the Mount Sholl area. Thickness and facies variations are a pronounced feature of the Duffer Formation. At Marble Bar the formation is between 4 and 8 km thick but it thins northwards to about 2 km near Coppin Gap. This attenuation is a primary stratigraphic feature since it is not accompanied by evidence of increased strain; in fact the reverse is true. Where the formation is thickest, agglomerate forms a large part of the succession, but thinner sections generally contain a greater proportion of lava and tuff. In the Mount Sholl-Whundo area the Duffer Formation is approximately 5 km thick and is composed chiefly of dacitic lava and tuff with numerous intercalations of basalt. Large outcrops of agglomerate occur 7 km south of Mount Sholl. In the Nickol River—Mount Princep area the Duffer Formation consists of an upper member of felsic lava and tuff underlain by clastic sediments and tuff. Some of the sedimentary rocks are well sorted but most are composed of lithic fragments and resemble greywacke; such rocks are exposed at the Lower Nickol mining centre. Volcanic centres responsible for the various wedge-shaped piles which collectively comprise the Duffer Formation were located at Marble Bar, Copper Hills, McPhee Creek and Mount Sholl. Between Glen Herring and Mount Sholl the formation is developed only thinly at Pilbara mining centre, Farrel Well and Lalla Rookh mining centre. Thus in many parts of the Pilbara Block the Duffer Formation is absent and the Mount Ada Basalt is overlain disconformably by the Towers Formation (e.g. North Pole and Pilgangoora mining centres, and Glen Roebourne).

Fitton and others (1975) did not recognize the Duffer Formation at Pilbara mining centre but their description of the Friendly Creek Formation (their appendix of stratigraphic definitions) reads as follows "Lower 600 m sheared chloritic metabasalts and gabbro, then 20 m banded chert followed by 600 m of felsic tuffs". The Friendly Creek Formation is overlain by the Hong Kong Chert (correlative of the Marble Bar Chert Member) and there seems little doubt that, in view of additional similarities to the Marble Bar succession (Plate 2), the felsic tuff represents the Duffer Formation and the metabasalt forms part of the Talga Talga Subgroup.

The formation has considerable metallogenic importance in the Pilbara Block. With the notable exceptions of Whim Creek and Mons Cupri, most of the area's copper deposits occur in the unit, or, where the unit is absent, at the stratigraphic level which approximates to the top of the Duffer Formation (Figure 50). Lead, zinc and barite deposits also occur at this level (e.g. Big Stubby, Yandicoogina and North Pole).

The top of the Duffer Formation is generally defined by the base of the lowest chert member of the Towers Formation. At Chinaman Pool this is a chert underlying the Marble Bar Chert Member, but in many areas the latter forms the stratigraphic marker. The base of the formation is marked by units of chert or basalt at the top of the Mount Ada Basalt.

The age of the Duffer Formation has been directly established by Pidgeon (1978 a) who dated zircons from columnar dacite from Glen Herring at 3 453 ± 16 m.y. by the

U-Pb method, and Sangster and Brook (1977) who dated galena from Big Stubby, 6 km south of Marble Bar, at 3 500 m.y. by the Pb-Pb method.

Pyroclastic rocks of the Duffer Formation consist of coarse euhedral plagioclase (now albite) laths which are up to 3.5 mm long and are commonly fractured and broken, autolithic fragments and minor anhedral quartz grains, set in a groundmass of quartz, albite and sericite, plus minor epidote, chlorite and scattered opaque minerals. Most traverses across the formation reveal moderately well-preserved ignimbritic units containing devitrified glass shards (Fig. 13), but ignimbrite is especially developed in the upper part of the formation at Bowls Gorge and in the Copper Hills area. Concentrations of plagioclase crystals in the pyroclastic rocks commonly produce poorly defined microscopic layering.

Dacitic lava is generally porphyritic and may contain small plagioclase microlites defining a flow structure.

All the rocks have undergone greenschist facies metamorphism but primary textures are preserved in non-schistose rocks. Plagioclase phenocrysts are commonly represented by sericite pseudomorphs and carbonatization is present in most rocks.

Towers Formation

The Towers Formation (Hickman, 1977c) is the main stratigraphic marker unit of the Warrawoona Group. Although the formation is generally only 0.5 km thick, it can be traced from Reedy Creek in the east to Devil Creek in the west, a distance of 430 km (Plate 2). As noted previously, outcrop is not continuous but the Towers Formation is lithologically quite distinct from other parts of the sequence. Where fully developed, it consists of three chert members (prominent on the ground and on air-photographs) separated by two members of pillow basalt, felsic tuff or sedimentary rocks; felsic tuff and sedimentary rocks are dominant only in the west Pilbara. The central chert which is the thickest and most distinctive unit, is named the Marble Bar Chert Member (Hickman, 1977c).

The type section of the formation is located at Towers mine where the two volcanic units separating the chert members each consists of a lower basaltic section and a thin felsic top. Ultramafic rocks are locally developed, but it is uncertain if these are intrusive or extrusive. At Marble Bar Pool, Kjellgren (1976) identified pillow komatiite between the lowest chert and the Marble Bar Chert Member. The latter is approximately 100 m thick at Marble Bar Pool (the best, and most easily accessible, locality for examining the member) and consists of red and white banded and/or grey and white banded chert.

In most parts of the Pilbara Block all three or at least two of the chert units comprise the Towers Formation, but at some localities (e.g. Camel Creek at the northern margin of the Corunna Downs Batholith) only one chert unit is preserved. No chert unit has been located at this stratigraphic level between Mount Sholl and Mount Roe. This fact does not discredit the stratigraphic correlations involved because the Towers Formation also wedges out betwen Marble Bar and Coppin Gap, where the outcrop of the Duffer Formation is continuous.

At Pilbara mining centre Fitton and others (1975) correlated at 50 to 150 m thick chert unit (Hong Kong Chert) overlying the Friendly Creek Formation with the Marble Bar Chert Member of the east Pilbara. Two parallel ridges of chert south of Hong Kong mine are stated to be the Hong Kong Chert duplicated by an isoclinal anticline. However, pillow structures which the writer has observed to the south of the southern chert suggest that facing is to the north and the two chert units are consequently separate horizons. The Towers Formation in this area is represented by two, and locally three, chert members rather than one (Plate 2).

Ingram (1977) considered that the Marble Bar Chert Member is the highest unit of a mafic-felsic cycle (Sharks Formation) and that the overlying basaltic succession rests uncomformably on it. The writer knows of no locality where this unconformity may be observed, but the existence of such a stratigraphic break would explain local disappearances of the Towers Formation. It is notable, for example, that at Marble Bar Pool the Marble Bar Chert Member forms the top of the formation, the upper chert at Towers mine having wedged out northwards over a distance of only 13 km. Farther north the upper chert reappears.

Kjellgren (1976) concluded that the Marble Bar Chert Member at Marble Bar Pool was precipitated as a silica gel in a low energy environment such as a hypersaline lake or restricted marine basin, but Dunlop (1976; Dunlop and others 1978) considered that the lowest chert member of the Towers Formation at North Pole mining centre probably originated by early diagenetic silicification of carbonate sediment. At North Pole, Dunlop (1976) reported algal-like fabrics and abundant carbonaceous matter in the chert, and organic material in associated sedimentary barite. Dunlop's case for carbonate silicification at North Pole is fairly compelling, but as noted by Hickman (1973), the apparent absence of carbonate relicts (other than scattered grains) is not easily explained. Moreover, there are no carbonate deposits, stratiform or otherwise, in the successions above or below so that vast amounts of material must have been completely removed from the area. It seems probable that, on a regional scale, virtually all the chert units of the Towers Formation were deposited as silica gels, but lenses of carbonate sediment, perhaps containing algal fossils, were probably developed at a few localities (see also page 173).

Apex Basalt

The Apex Basalt (Hickman, 1977c) forms the lower part of the Salgash Subgroup between Apex mine and Warrawoona mining centre. The type section of the formation follows Chinaman Creek from the top of the Marble Bar Chert Member (locally equivalent to the top of the Towers Formation) at Marble Bar Pool westwards for 2 km to the base of a felsic lava-chert unit constituting the Panorama Formation.

The Apex Basalt is generally 1 500 to 2 000 m thick and consists of tholeiitic pillow basalt, high-magnesium basalt (tremolite-chlorite rocks), peridotitic komatiite, several thin members of grey and white banded chert, and sills of dolerite, gabbro and rare altered ultramafic rocks. The regional distribution of the formation is similar to that of the underlying Towers Formation. Although its rocks are lithologically indistinguishable from other basalt formations of the Warrawoona Group, the unit can generally be quite easily identified on stratigraphic grounds; that is, it is always (a) underlain by the Towers Formation and/or the Duffer Formation, and (b) overlain by thin felsic volcanics, chert, or metasediments (Panorama Formation) followed by another thick basalt formation (Euro Basalt) which in turn underlies rhyolite (Wyman Formation) and BIF (Cleaverville Formation).

The petrography of rock types forming the Apex Basalt had been described above (see section, "Mafic Volcanic Rocks", in Chapter 2) and is not repeated here. The chemistry of the formation is summarized in Appendix F.

Panorama Formation

The Panorama Formation (Hickman and Lipple, 1975; Lipple, 1975) is a central marker within the Salgash Subgroup. The formation consists of felsic lava, tuff, agglomerate, chert and metasediments in the east Pilbara, but in the west Pilbara it is chiefly composed of chert and tuff. Its general thickness is 100 to 1 000 m in the east Pilbara but only 10 to 100 m in the west Pilbara.

At Kelly mine, 20 km south of Copper Hills, a correlated unit of prophyritic and vesicular dacitic lava, tuff and agglomerate with minor chert is named the Kelly Formation (Hickman and Lipple, 1975; Lipple, 1975). Some of the dacite at this locality exhibits columnar jointing.

The type area of the Panorama Formation is Panorama Ridge situated 6 km northeast of the North Shaw mining centre. Here the lower and western parts of the formation are composed of dacitic lava, tuff and agglomerate, whereas quartzite and chert predominate in the upper and eastern sections. A marked facies change occurs at Shaw Gorge where the felsic volcanics interfinger and pass southwestwards into a clastic succession of conglomerate, sandstone and shale. Excellent exposures of coarse polymictic conglomerate are available in the gorge; clasts range in composition from basalt to dacite, chert, quartzite and vein quartz, and cross-bedding is a common feature of the sandstone units. It must be pointed out, however, that some doubt exists as to the stratigraphic position of this Shaw Gorge sequence which could belong to the Duffer Formation.

Fitton and others (1975) noted that their "Empress Formation" (Table 3) contains "a thin but persistent chert unit" with "a known strike length of at least 60 km". This chert is said to separate a lower assemblage of mafic and ultramafic lavas from an upper unit of similar lithology. A central chert formation also divides the Salgash Subgroup between Karratha and Devil Creek, and Geological Survey mapping of the Roebourne Sheet (Ryan 1966) revealed a unit of felsic tuff in the centre of the thick basaltic pile west of Mount Roe. These chert and tuff units are probable correlatives of the Panorama Formation.

Euro Basalt

In most parts of the Pilbara Block the Euro Basalt (Hickman, 1977c) is lithologically indistinguishable from the Apex Basalt. The formation's thickness is generally about 2 000 m. Southwest of Euro mine the type area contains pillow basalt with minor chert and felsic lava. Dolerite and gabbro sills are less common than in the Apex Basalt. Quartz-carbonate-chlorite rock occurs at the top of the formation at Camel Creek and Sandy Creek and may represent altered ultramafic lava. Spinifex-textured basaltic rocks containing tremolite, chlorite, epidote and clinozoisite make up the bulk of the formation south of Camel Creek. Some of these rocks represent high-magnesium basalt but in general the Euro Basalt of the east Pilbara appears to be less mafic than the Apex Basalt. Near Pilbara mining centre the lower part of the Euro Basalt is composed of peridotitic komatiites (Fitton and Fitton, 1976) with spinifex-textured flow tops, chilled bases and occasional pillow structures. At Karratha the formation is represented by poorly foliated amphibolite (metabasalt). Lenticular structures in the amphibolite may represent flattened pillow structures, but no clear facing evidence has been observed.

At Kelly mine, Wyman Well and Wallabirdee Ridge the Euro Basalt is unconformably overlain by the Wyman Formation, but at Strelly Pool, the Coongan Belt and Pilbara mining centres, the two units appear to be conformable. At present it is assumed that this regional variation is a product of local deformation during deposition of the Warrawoona Group, but future studies may establish a regional stratigraphic break at this level.

Wyman Formation

The Wyman Formation (Hickman and Lipple, 1975; Lipple, 1975) is composed chiefly of porphyritic rhyolite flows but the unit also contains local tuff, agglomerate and minor basalt (e.g. on the eastern side of the Strelley Granite). The type area is situated south of Wyman Well, in the centre of the Warrawoona Syncline. Excellent exposures of porphyritic columnar rhyolite (Fig. 11) are available at Camel Creek. Columnar rhyolite is also prominent in the Kelly mining centre and Wallabirdee Ridge areas.

Some doubt now exists as to the validity of including the Wyman Formation in the Warrawoona Group. As noted elsewhere in this bulletin (e.g. Chapter 6), in certain areas it unconformably overlies older units of the group, but in the type area and elsewhere it is concordant with the Euro Basalt. In the absence of any reliable geochronological evidence on the Wyman Formation the present interpretation is that local unconformities reflect local deformation, and that deposition was continuous over parts of the block.

The normal thickness of the Wyman Formation is 500 to 1 000 m. It is not surprising that such a thin formation of rhyolite, presumably extruded as relatively viscous lava, is absent from the succession in many parts of the Pilbara Block; in fact, the presence of the unit in such widespread areas as Nunyerry Gap, Pilbara mining centre, Pincunah, Strelley Pool, Soanesville (15 km north), Wyman Well, Coppin Gap, Kelly, Spinaway Well, Wallabirdee Ridge and Mount Elsie (8 km west) testifies to a remarkable contemporaneous outpouring of rhyolite lava from a large number of vents scattered across the craton.

Euhedral phenocrysts of beta-quartz and potash feldspar set in a ground mass of quartz, simply twinned potash feldspar and sericite, with minor epidote and chlorite, make up the porphyritic rhyolite units. The beta-quartz grains possess corroded or embayed edges. Potash feldspar phenocrysts, partly altered to sericite, are commonly perthitic, and are thought to have been anorthoclase which has inverted to microcline and exsolved a sodic plagioclase. Sericite in the groundmass commonly has a weak orientation and small potash feldspar laths are locally aligned to impart a trachytic texture to the rock. Rhyolite from Budjan Creek possesses a perlitic texture (Fig. 10) and both at this locality and Emu Creek (Kelly area) the rock possesses a considerable amount of secondary silica in the form of veins or clots.

The chemistry of the Wyman Formation is very different from that of the Duffer Formation and indicates derivation from a quite highly fractionated magma (see Chapter 5).

GORGE CREEK GROUP

Noldart and Wyatt (1962, p. 105) used the name "Gorge Creek Formation" to refer to a succession of quartzite, conglomerate and BIF which crops out between Yarrie homestead, Gorge Creek, and the headwaters of Strelley River. Hickman and

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TABLE 4. STRATIGRAPHIC SUBDIVISION OF THE GORGE CREEK GROUP

East Pilbara			*West Pilbara*		
Formation	*Thickness (km)*	*Lithology*	*Formation*	*Thickness (km)*	*Lithology*
Mosquito Creek Formation	>5.0	Psammitic to pelitic schistose rocks. Greywacke and turbidites. Minor sandstone and conglomerate.	"Mallina Formation"	>5.0	As Mosquito Creek Formation.
Lalla Rookh Sandstone	0-0.5	Sandstone, grit and conglomerate.	"Constantine Sandstone"	0-3.0	As Lalla Rookh Sandstone.
Honeyeater Basalt	0-1.0	Pillow basalt containing sills of dolerite and gabbro. Minor high-magnesium basalt.			
"Paddy Market Formation"	0.5-1.0	As Cleaverville Formation.	Cleaverville Formation	0-1.0	BIF, and ferruginous chert and shale.
Charteris Basalt	0-1.0	Pillow basalt, minor high-magnesium basalt, and dolerite. Local thin units of chert and felsic lava.			
Corboy Formation	1.0-2.0	Quartzite, sandstone, psammopelite and ferruginous sediments.			

Lipple (1975) renamed this unit the Gorge Creek Group because it contains several distinctive mappable units. The Mosquito Creek Formation (Table 4) is not present at Gorge Creek, or in the group's type area between Gorge Creek and Soanesville, but Hickman and Lipple provisionally included it in the group because they considered that it might partly be a facies variation of the Lalla Rookh Sandstone.

In the west Pilbara the Gorge Creek Group is entirely composed of schistose psammitic to pelitic rocks, sandstone and BIF, but farther east the unit includes wedge-shaped formations of basaltic rock. Gabbroic and ultramafic sills are relatively common in the lower part of the succession in the east Pilbara but in the west are concentrated in the Mosquito Creek Formation (Mallina Formation of Fitton and others, 1975).

Thickness variations and facies changes are far more prevalent in the Gorge Creek Group than in the Warrawoona Group. Chemical sediments and fine-grained clastic rocks are largely restricted to the lower part of the succession, and the bulk of the group appears to have accumulated in an unstable tectonic environment. Earth movements probably commenced shortly after extrusion of the Honeyeater Basalt, which is unconformably overlain by the Lalla Rookh Sandstone southeast of Strelley Pool. The Mosquito Creek Formation is a poorly sorted deposit derived by rapid erosion of the Warrawoona Group. At McPhee Creek the formation rests unconformably on the Duffer Formation, a fact which proves deep erosion of the Warrawoona Group at this particular locality. Further evidence of extensive erosion of the Warrawoona Group comes from the Doolena Gap area where granite pebbles up to 200 mm in diameter occur in conglomerate of the Lalla Rookh Sandstone. Granite pebbles were also noted by Fitton and others (1975, p. 17) in the same unit near Croydon. Unless the granite was derived from high relief inliers never covered by the deposits of the Warrawoona Group (improbable in view of the thickness of the latter), it must have been eroded either from beneath (basement granite) or within (intrusive granite) that unit.

Table 2 indicates that the contact between the Gorge Creek Group and the Warrawoona Group is not an unconformity in certain parts of the craton. Where the Corboy Formation overlies the Wyman Formation near Strelley Pool and several other localities, the two units are bedded concordantly and there is no evidence of an unconformity. Elsewhere, however, such as at Mosquito Creek and Farrel Well (9 km southwest) the two groups are unconformable. Although the Wyman Formation is absent in the Warralong Creek-Doolena Gap area and in most areas to the west of Pilgangoora, these parts of the block may contain contemporaneous basaltic lava locally forming the top of the Euro Basalt. The same argument of facies variation, without any pause in deposition, can be applied in situations where the Corboy Formation is absent; it might be a lateral facies equivalent of the lower part of the Cleaverville Formation. In the Soanesville area the Corboy Formation and the Cleaverville Formation are represented by a mixed succession of sandstone, siltstone, ferruginous shale, BIF and basalt, which Lipple (1975) formally defined as the Soanesville Subgroup. Northwards from the Soanesville area, the subgroup, which Lipple estimated to be between 5 and 8 km thick, changes facies so that the Corboy Formation (sandstone) and the Cleaverville Formation (BIF and ferruginous sediments) area easily distinguishable.

The boundary between the Gorge Creek Group and the overlying Whim Creek Group is exposed only in the Whim Creek-Sherlock River area where there is strong evidence for an angular unconformity (Fitton and others, 1975; Hickman, 1977d). Mr

S. L. Lipple (pers. comm.) considered that the Whim Creek Group may also be preserved 13 km northwest of Soanesville (Plate 1B) where felsic volcanics rest unconformably on the lower part of the Gorge Creek Group. If this correlation is correct, a regional unconformity must exist between the two groups.

The Archaean age of the Gorge Creek Group is directly established 10 km east of Cooke Bluff Hill, where tightly folded Lalla Rookh Sandstone is unconformably overlain by the Mount Roe Basalt (basal formation of the Fortescue Group). Similar unconformities exist near Blue Bar mine, Warralong Creek, Twenty Ounce Gully, and Yandicoogina. The Mosquito Creek Formation is unconformably overlain by the Fortescue Group at Nullagine (as noted by Maitland, 1905) Eastern Creek (8 km southeast), Whim Creek (10 km east), Egina, Station Peak and Nunyerry Gap.

Corboy Formation

The Corboy Formation (Hickman and Lipple, 1975; Lipple, 1975) consists of quartzite, sandstone and psammopelitic rocks. Psammopelitic rocks and ferruginous metasediments predominate in the type area around Corboy mining centre, but in most other areas (Plate 1) siltstone, sandstone and quartzite predominate. The thickness of the formation ranges up to 2 000 m. In the west Pilbara the unit is absent, although it may be locally represented by sandstone which overlies amphibolite (?metabasalt) in the core of an anticline, 25 km southwest of Station Peak. Facies changes, already described, occur between Strelley Pool and Soanesville, and northwards along the length of the Coongan Syncline (see section "Sedimentary Rock (not subdivided)" in Chapter 2). About 5 km northeast of Cooke Bluff Hill a succession of sandstone and ferruginous shale, siltstone and conglomerate which underlies the Cleaverville Formation (Hickman, 1977 b) is correlated with the Corboy Formation.

Cross bedding is common in the sandstone beds of the formation, but no attempt has been made to determine palaeocurrent directions.

Charteris Basalt

Mapping of the Nullagine 1:250 000 Sheet in 1973 revealed the existence of the succession of basaltic rocks conformably overlying rocks correlated with the Corboy Formation. Between Charteris Creek and Sandy Creek, the formation's type area, the Charteris Basalt crops out over 50 km^2 of country and ranges in thickness from 500 to 2 000 m. This variation appears to be partly due to deformation, and the primary thickness is estimated to have been 1 000 m. Pillow tholeiitic basalt and high-magnesium basalt make up the bulk of the succession; most of the basalts analysed from this area contain between 8.0 and 12.0 per cent MgO. Dolerite sills are relatively common and thin units of felsic lava and chert occur near the top of the formation. Outside the Charteris Creek area the formation has been identified only at Warralong Creek where it is interposed between the Corboy Formation and the Lalla Rookh Sandstone. This is also the situation in the northern part of the type area, but farther south, around the headwaters of Sandy Creek, BIF of the Cleaverville Formation overlies the Charteris Basalt. The wedge-shaped geometry of the formation, and the fact that more than one unit immediately overlies it in various localities, suggests that locally its upper contact may be a low-angle unconformity.

Cleaverville Formation

The Cleaverville Formation (Ryan and Kriewaldt, 1964) is composed chiefly of BIF, ferruginous chert and ferruginous shale. The formation was first recognized as a discrete mappable unit in the Roebourne-Cleaverville area, although the existence of BIF in the Gorge Creek Group had previously been noted by Noldart and Wyatt (1962). As mentioned above, Noldart and Wyatt combined the unit with standstone and conglomerate under the name "Gorge Creek Formation", a sequence of rocks which, in the type area at Gorge Creek, now includes the Corboy Formation and the Lalla Rookh Sandstone. Low (1963) correlated BIF at Goldsworthy with the BIF at Gorge Creek, and Ryan (1965) extended the correlation to include the Cleaverville rocks. In the Marble Bar area, Hickman and Lipple (1975) named BIF and associated ferruginous sediments in the Gorge Creek Group the "Paddy Market Formation" (formally defined by Lipple, 1975). This name could still be applied to rocks at Paddy Market Creek, but regional mapping of the Pilbara Block has left little doubt that the "Paddy Market Formation", the BIF at Gorge Creek and Goldsworthy, and the Cleaverville Formation of the west Pilbara are all the same formation. Because the name Cleaverville Formation has historical precedence it is now applied across the Pilbara Block.

The Cleaverville Formation is an exceptionally thick BIF by Archaean standards. BIF units in the Yilgarn Block rarely exceed 100 m, but at Cleaverville, Roebourne, Ord Range, Goldsworthy, Shay Gap, Yarrie homestead, Strelley Pool (10 km southwest), Honeyeater Creek, Pincunah, Paddy Market Creek and Blue Bar this unit commonly approaches 1 000 m. Certainly, true BIF generally alternates with ferruginous chert and minor grey and white banded chert but the average iron content across such sequences probably exceeds 30 per cent. In some areas BIF partly results by surface silification of ferruginous shale. Drilling in the Ord Range, for example, has revealed underlying pyritiferous black shale. Elsewhere, such as Goldsworthy and Shay Gap, the BIF units persist down dip for many hundreds of metres and are not known to "bottom out".

Various aspects of Archaean BIF in the Pilbara Block, including accessible exposures, composition, iron enrichment and origin are discussed earlier (see section "Banded Iron-Formation and Ferruginous Chert", in Chapter 2).

Honeyeater Basalt

The Honeyeater Basalt (Lipple, 1975) crops out between Honeyeater Creek and Strelley Pool, in the Soanesville Syncline, 3 km east of Copping Gap, and at Shay Gap. Ranging in thickness to about 1 000 m, the formation is composed of pillowed tholeiitic basalt with subordinate high-magnesium basalt, and contains dolerite and gabbro sills. The type area is designated (Lipple, 1975) as being adjacent to Honeyeater Creek, but more extensive exposures are available in the Soanesville and Shay Gap areas. Chemical analyses of samples from the Soanesville area have confirmed a high magnesium content in many of the pillow lavas which were provisionally identified as basaltic komatiites on the basis of fine spinifex textures. Microscopic examination revealed that some of the lavas contain fine-grained prehnite (Fig. 16) and pumpellyite indicating low-grade metamorphism.

Lalla Rookh Sandstone

The Lalla Rookh Sandstone (Hickman and Lipple, 1975; Lipple, 1975) ranges up to 5 000 m thick and is composed entirely of sandstone, quartzite and conglomerate. The type area of the unit is the Lalla Rookh Syncline between Lalla Rookh mining centre and Honeyeater Creek, but the succession is also exposed, with less structural complication, between Cooke Bluff Hill and Gorge Creek (Plates 1B and 2). Well-sorted, but slightly feldspatic, sandstone is the dominant lithology. The rock is generally bedded at intervals of 0.1 to 1.0 m and commonly exhibits cross-bedding (Fig. 6). Palaeocurrent analysis at North Pole suggests that the prevailing transport direction was locally south to north (J. Nicholson, pers. comm.). Comments on petrography and depositional environment are made in the section "Sandstone and Conglomerate", in Chapter 2.

Plate 1B shows the regional distribution of the Lalla Rookh Sandstone. In the West Pilbara Fitton and others (1975) correlated it with sandstone at Mount Constantine, but argued that the Constantine Sandstone and the overlying Mallina Formation (Mosquito Creek Formation) are part of the Whim Creek Group. This interpretation was criticized by Hickman (1977d) who presented evidence to show that the Mosquito Creek Formation underlies the Whim Creek Group.

The Constantine Sandstone is lithologically indistinguishable from the Lalla Rookh Sandstone and is conformably overlain by rocks correlated with the Mosquito Creek Formation. At Nunyerry Gap and Pilbara mining centre it is uncomformably underlain by the Cleaverville Formation (Fitton and others, 1975), which in turn rests on porphyritic rhyolite of the Wyman Formation. Accordingly, there are good stratigraphic grounds to correlate the Lalla Rookh Sandstone with the Constantine Sandstone, and the latter name may be legitimately suppressed when discussing the regional stratigraphy of the Pilbara Block.

Noldart and Wyatt (1962, p. 102) named a succession of sandstone, siltstone, conglomerate and shale in the Copper Hills–Kelly area the "Budjan Creek Formation". They described this unit as disconformably overlying the Warrawoona Group and being unconformably overlain by the Beaton's Creek Conglomerate (Hardey Sandstone of the Fortescue Group). Lipple (1975) correlated the "Budjan Creek Formation" with the Lalla Rookh Sandstone, and added that the unit unconformably overlies the Warrawoona Group. At Budjan Creek the unit occupies the core of a syncline which extends northeastwards under Proterozoic cover to re-emerge 10 km north of Lionel. Here the sandstone overlies a thin development of BIF (Cleaverville Formation) and has been correlated with the Lalla Rookh Sandstone (Hickman, 1975a). BIF is preserved 5 km south of Copper Hills, and BIF and chert occur in the eastern limb of the sycline near Budjan Creek. The absence of BIF and chert along the greater part of the syncline's western limb is attributed to an unconformity at the base of the sandstone formation.

Fitton and others (1975, Appendix) suggested that the age of the Lalla Rookh Sandstone is between 2 500 and 2 300 m.y. based on their correlation of the unit with part of the Whim Creek Group. Plate 1B shows, however, that the Satirist Granite appears to intrude and dilate the core of a north-trending anticline which contains the succession Mosquito Creek Formation–Lalla Rookh Sandstone–amphibolite (?metabasalt). As noted in the section "Granitic Rocks", in chapter 2, the Satirist Granite contains two rock types: gneissic granitic rocks in the north, and porphyritic adamellite in the centre and south. The gneissic granite is well foliated and resembles rocks of the older granitic complex (3 000+ m.y. in age) yet it intrudes the surrounding layered sequence. The prophyritic adamellite is weakly foliated and lithologically resembles rocks which, in the East Pilbara, are intermediate in age between the oldest granitic rocks and the post-tectonic granites. Moreover, Leggo and others (1965) dated the porphyritic adamellite part of the Satirist Granite at 3 040 m.y. Although the reliability of this result is impaired by its being derived from a single Rb-Sr determination, the overall chemistry of the adamellite (especially with respect to its Rb/Sr ratio) is closer to that of the older complex than to post-tectonic rocks. In summary, the Satirist Granite is best interpreted as a forceful, pre- or syn-tectonic mass and the Lalla Rookh Sandstone is therefore, probably close to 3 000 m.y. in age. Structural criteria add weight to this conclusion. The Croydon Anticline and folds on the southern side of the Satirist Granite are relatively tight structures, quite distinct from those in the Whim Creek Belt. They were probably formed during the main episode of deformation, D2, which Oversby (1976) has suggested may have reached a climax at about 2 950 m.y. ago.

In the east Pilbara, between Pilgangoora and Wodgina, the Lalla Rookh Sandstone is intruded by well-foliated migmatitic granodiorite, which farther southwest is intruded by the post-tectonic Numbana Granite.

Mosquito Creek Formation

Previous usage of the name "Mosquito Creek" in variously classifying the distinctive succession of metasediments east of Nullagine as a Series, System, Succession or as Beds is summarized in Chapter 1. The most detailed description of the unit is provided by Noldart and Wyatt (1962, p. 102-107) who named it the "Mosquito Creek succession". Noldart and Wyatt referred to five component formations and consequently appear to have regarded the unit as a group (present nomenclature). Hickman (1975a) redefined the unit as a formation because it is composed essentially of one principal rock type, and because further subdivision into discrete mappable units of known relationship is not yet possible. Three of Noldart and Wyatt's subdivisions were laterally equivalent basal units, and the bulk of the outcrop does not appear to have been assigned to any of the five formations.

The Mosquito Creek Formation consists of schistose psammitic, psammopelitic and pelitic metasediments with minor conglomerate units. In all but the most psammitic beds the dominant foliation of the rocks is a cleavage related to east-west trending isoclinal folds. The chief rock type is poorly sorted wacke-siltstone and wacke-sandstone intercalated at 0.5 to 1.0 m intervals with more pelitic material. Graded bedding is extremely common and generally can be detected wherever bedding planes are discernible. Exposures are numerous across the 1 800 km^2 outcrop east of Nullagine, but are generally small and rather disappointing sedimentologically. Strike ridges of relatively psammitic rock are typically separated by colluvial valleys underlain by more pelitic rocks. The ridges are deeply weathered, lithologically monotonous and commonly show effects of surface creep. They rarely provide satisfactory exposures of sedimentary structures, and the latter must generally be sought in creek beds and shallow breakaways at the heads of tributary channels. Many such exposures display excellently preserved sedimentary structures of the type found in turbidite deposits, such as graded bedding, cross-bedding, scour structures and Bouma cycles.

The base of the Mosquito Creek Formation unconformably overlies the Warrawoona Group between the Lionel and Cooke Creek mining centres. Conglomerate, chert, minor mafic and felsic volcanics, and ultramafic rocks occur in the lowermost 1 000 m of the succession. At Eastern Creek the base of the formation is formed of sandstone and conglomerate (Plate 2), and is lithologically very similar to the Lalla Rookh Sandstone; indeed, lateral equivalence with that unit is quite probable.

The top of the Mosquito Creek Formation is not exposed but pelitic turbidites, which crop out in an easterly belt from Nullagine to the Middle Creek and Mosquito Creek mining centres, appear to lie in the core of the Mosquito Creek Synclinorium (Plate 1B) and are interpreted as the uppermost part of the preserved succession. Conglomerate beds at Dromedary Hill, 10 km south-southeast of Nullagine, are lenticular members within the formation, and no structural evidence has been found to support Noldart and Wyatt's (1962, p. 105) view that they represent the base of the unit.

The total outcrop area east of Nullagine is approximately 1 800 km^2 and the Mosquito Creek Formation appears to be at least 5 000 m thick. Accurate measurement of the formation's true thickness will be impossible until the complex system of isoclinal folds which deforms the succession has been mapped in detail.

In the west Pilbara a succession of strata lithologically similar to the Mosquito Creek mining centres, appear to lie in the core of the Mosquito Creek Synclinorium (Plate 1B) and are interpreted as the uppermost part of the preserved succession. 1975). Fitton and others correlated the Mallina Formation with the Mosquito Creek Formation on stratigraphic and lithological grounds already mentioned. Various previous workers have also noted the similarity between the two units and the correlation is now considered to be beyond reasonable doubt. The outcrop area of the Mosquito Creek Formation in the west Pilbara is approximately 5 000 km^2, but exposures are less common than in the type area east of Nullagine. Ryan (1965, p. 72) estimated its thickness to be 12 000 m, Miller (1975) suggested 10 000 m, and Fitton and others (1975) stated that the formation is only 2 500 m thick. These different interpretations give some indication of the difficulties involved in determining the true stratigraphic thickness of this poorly exposed, structurally deformed unit. The present estimate of 5 000 m (Table 4) is based on outcrop width, the general inclination of strata and the known distribution of major fold axes.

Several workers (Ryan, 1964; Ryan and Kriewaldt, 1964; Ryan, 1965; Miller, 1975; Fitton and others, 1975) stated that these sedimentary rocks were deposited in a major northeasterly trending trough or eugeosyncline. Poor sorting and rock composition testify to rapid deposition under unstable conditions, and much of the sequence was probably deposited from turbidity currents. As noted later, however, the depth and lateral extent of the depositional basin has yet to be firmly established. There are no grounds to assume that the limits of the present outcrop closely resemble those of the depositional basin. Moreover, the depositional area may have been an area of progressive subsidence rather than a deep-water trough.

Ryan (1965) stated that the Mosquito Creek Formation of the Croydon-Mallina area is overlain at Whim Creek by volcanics which pass laterally northeastwards into slate (e.g. at Whim Creek mine). Recent work by mineral companies and the Geological Survey, however, has established that the slate at Whim Creek mine (Rushall Slate) overlies the volcanics of the Whim Creek Belt.

Stratigraphic subdivision of the Mosquito Creek Formation of the west Pilbara is not attempted here. Ryan (1965) considered that mafic rocks, chert, and banded iron-formation which crop out at Mount Langenbeck, Station Peak and south of the Satirist Granite are lateral equivalents of the volcanics at Whim Creek and Roebourne. He regarded these rocks as occurring in the central part of the clastic succession. Work by Fitton (Fitton and others, 1975) has shown that the correlation of these beds with the Warrawoona Group at Roebourne and Pilbara mining centre must be abandoned because at Pilbara mining centre the lowest beds of the Mosquito Creek Formation overlie the Warrawoona Group. The stratigraphic position of the ferruginous rocks at Station Peak and Mount Langenbeck remains uncertain. Fitton and others (1975, Fig. 1) correlated them with the Cleaverville Formation (BIF of the lower part of the Gorge Creek Group) and interpreted them as inliers exposed in the cores of anticlines. Mapping by the writer suggested that, although the Mount Langenbeck rocks occur in an anticline, the ferruginous strata near Station Peak and farther southwest are underlain by clastic sediments of the Mosquito Creek Formation and Lalla Rookh Sandstone. In summary, Ryan's view that the ferruginous rocks occur within the Mosquito Creek Formation is thought to be correct, but their correlation with the Cleaverville Formation and Warrawoona Group is not accepted.

Evidence relating to the age of the Mosquito Creek Formation in the west Pilbara is the same as that for the Lalla Rookh Sandstone, that is the unit is probably close to 3 000 m.y. old. In the east Pilbara the base of the formation is intruded and metamorphosed by the Cookes Creek Granite (5 km east of Cookes Creek mining centre). De Laeter and others (1977) dated the Cookes Creek Granite at 2 600 m.y. Throughout the Pilbara Block the intensely folded Mosquito Creek Formation is unconformably overlain by relatively gently dipping strata of the Fortescue Group (Frontispiece and Plate 1B); isotope geochronology indicates that the basal part of the Fortescue Group is between 2 350 and 2 650 m.y. old.

WHIM CREEK GROUP

Fitton and others (1975) first defined the Whim Creek Group as a volcanic and sedimentary succession composed of four formations, the Warambie Basalt, Mons Cupri Volcanics, Constantine Sandstone and the Mallina Formation. As noted above, however the Constantine Sandstone and the Mallina Formation are now considered to form the upper part of the Gorge Creek Group. The Whim Creek Group is herein redefined as containing three formations: Warambie Basalt, Mons Cupri Volcanics, and Rushall Slate (new name).

Although this interpretation is supported by a considerable amount of stratigraphic, structural and geochronological evidence, debate on the subject continues, Horwitz (1979) maintaining that the definition by Fitton and others (1975) is correct. Accordingly, this section begins with a critical examination of Horwitz's arguments.

Central to the debate (Fitton and others, 1975; Hickman, 1977d; Horwitz, 1979) are (a) the existence or otherwise of a regional mid-Archaean unconformity above the Cleaverville Formation and (b) the stratigraphic position of the Warambie Basalt and Mons Cupri Volcanics in relation to the Constantine Sandstone and the Mallina Formation. The two opposing stratigraphic interpretations currently advocated are summarized in Table 10 of Hickman (1977d).

Evidence used by Fitton and others (1975) and Horwitz (1979) to support the concept of a regional mid-Archaean unconformity can be summarized as follows:
(1) An angular unconformity between relatively flat-lying Warambie Basalt and underlying deformed and metamorphosed rocks of the Warrawoona Group ("Teichmans Group") is visible 5 km west of Mount Fraser.
(2) Clasts of fuchsitic metasediments (derived chiefly from the Towers Formation) and banded iron-formation (Cleaverville Formation) occur in the Constantine Sandstone (Lalla Rookh Sandstone) at Teichmans gold mine and Croydon, and in a thin tuffaceous unit ("Cistern formation") at Mons Cupri.
(3) The granitic plutons of the west Pilbara are said to intrude all formations up to the Cleaverville Formation, and to have been accompanied by a "broad arching" of the sequence. Rare granitic pebbles occur in the Constantine Sandstone, and granitic fragments occur in the Mons Cupri Volcanics.

Close examination of these three lines of evidence reveals that although each establishes the existence of local stratigraphic breaks none provides proof of a single regional unconformity. Most important is the nature of the boundary between the Cleaverville Formation and the Lalla Rookh Sandstone across the Pilbara Block. If a regional unconformity existed at this level, one would expect the Lalla Rookh Sandstone to overlie a range of formations, generally with a pronounced angular unconformity. That this is not the situation can be seen on Plate 1B, and also on Figure 2 of Fitton and others (1975). In almost all areas where the Lalla Rookh Sandstone is preserved it directly overlies the Cleaverville Formation (one exception occurs in the area of the Teichmans gold mine where the Lalla Rookh Sandstone overlies the Warrawoona Group (Fitton and others, 1975) and another in the Strelley-Soanesville area where the Honeyeater Basalt intervenes). Moreover, both formations are deformed concordantly by tight to isoclinal D2 folds; structures, incidentally, which almost certainly formed at about 2 950 m.y. (Oversby, 1976), some time before deposition of the Mons Cupri Volcanics (approximately 2 700-2 330 m.y. old, on present evidence).

Fitton and others (1975, p. 15) referred to a good example of the "regional unconformity" in the Copper Hills area where steeply inclined strata of the Warrawoona Group are said to be unconformably overlain by "a sequence of sandstones and conglomerates which we correlate with the Constantine Sandstone". In fact, two unconformities exist at this locality (Budjan Creek), the lower and most angular being a stratigraphic break at the base of the Wyman Formation (a unit which underlies the Cleaverville Formation). About 15 km northeast of Budjan Creek the Cleaverville Formation and the Lalla Rookh Sandstone are concordant and dip steeply eastwards.

According to Fitton and others (1975) and Horwitz (1979) the "mid-Archaean regional unconformity" is intruded by ultramafic to mafic sills ("Millindinna Complex") over 40 000 km^2 of the Pilbara Block. As noted previously (e.g. page 77), however, such intrusions occur at many stratigraphic levels in the Pilbara Supergroup. Present geochronological information is insufficient to justify selective grouping and correlation of intrusions from any particular level. The term "Millindinna Complex" would be useful to collectively refer to the sills which intrude the Mallina Formation in the area around Millindinna Hill and Station Peak.

The second major subject of debate is the stratigraphic position of the Warambie Basalt and the Mons Cupri Volcanics (Hickman, 1977d, Table 10). Fitton and others

(1975) and Horwitz (1979) argued that slate and phyllite (Rushall Slate in this bulletin) at Whim Creek mine and Mons Cupri belong to the Mallina Formation. Because this slate overlies the Mons Cupri Volcanics the conclusion drawn was that the Mons Cupri Volcanics and the underlying Warambie Basalt must be older than the Mallina Formation and the Constantine Sandstone. Previous stratigraphic interpretations (Ryan, 1965; Miller, 1975), however, placed the Rushall Slate at a higher stratigraphic level than the Mallina Formation.

Direct correlation between the Mallina Formation (i.e. the succession between Mallina and Croydon) and the Rushall Slate is prevented by major strike faults (Plate 1B). The correlation appears to be based on the fact that the Mallina Formation includes some pelitic metasediments which broadly resemble the Rushall Slate, and a structural interpretation of the area south-southwest of Mons Cupri. Unfortunately the correlation presents major problems in relating the succession of the Whim Creek-Mons Cupri area to that immediately southeast of the faults. Firstly, the Mons Cupri Volcanics and the Warambie Basalt do not occur in the southeast, and secondly, the Constantine Sandstone is absent in the Whim Creek-Mons Cupri area. To explain these fundamental stratigraphic differences Fitton and others (1975) and Horwitz (1979) invoked abrupt facies changes across the faults. Evidence to support these facies changes is limited to the occurrence of rare porphyritic rocks (of uncertain nature and origin) between Mount Satirist and Millindinna (Horwitz, 1979), and the presence of a thin and impersistent tuffaceous unit (also of uncertain origin) at the top of the Mons Cupri Volcanics. Referring to this tuffaceous unit, the "Cistern formation" of Miller and Gair (1975), Horwitz stated: "this unit correlated with the Constantine Sandstone by Fitton and others (1975, p. 17) has caused much geological debate; it does intrude, or mix with, the underlying fragmentals, but on petrological examination it is essentially a tuffaceous grit." Miller and Gair, however, stated that " . . . it is either a sill or a welded tuff bed", and that " . . . the top portion of the unit contains silicified fragments of the Whim Creek slate" (Rushall Slate). In summary not only does the "Cistern formation" differ from the Constantine Sandstone in thickness and lithology, but its actual origin as a sediment remains uncertain.

Closer examination of the general lithological characteristics of the Mallina Formation and the Rushall Slate (see relevant sections of this bulletin) reveals that whereas the former is chiefly composed of fairly coarse-grained turbiditic sediments, the latter is fine grained and contains several volcanic units. The thicknesses of the two units also differ, the Mallina Formation being about 5 000 m and the Rushall Slate being only 200m thick.

Direct evidence that the Rushall Slate and the Mallina Formation occur at different stratigraphic levels is available 15 km southeast of Sherlock homestead (Hickman, 1977d). Here a 500 m thick unit of felsic agglomerate, tuff and flow-banded dacite overlies a thick unit of turbiditic metasediments. Horwitz (1979) accepted Hickman's (1977d) interpretation that the felsic rocks belong to the Mons Cupri Volcanics and that the sediments form part of the Mallina Formation. Since at Whim Creek the Rushall Slate clearly overlies the Mons Cupri Volcanics, the problem would appear to be resolved. Horwitz, however, suggested that the Rushall Slate at Mons Cupri and the metasediments southeast of Sherlock form part of a single unit extending uninterrupted beneath the 6 km wide outlier of Negri Volcanics southwest of Mons Cupri (Plate 1B). Whether this is the situation or not cannot be conclusively established from surface geology, but three lines of evidence suggest that there is a discontinuity beneath the Negri Volcanics, and that Hickman's (1977d) interpretation is correct:

(1) The metasediments southwest of Negri Volcanics lithologically resemble the Mallina Formation farther to the west and south, whereas those at Mons Cupri contain a considerable proportion of pyroclastic material.

(2) The southwestern metasediments are more strongly deformed than those at Mons Cupri, bedding commonly being inclined at 60-70 degrees.

(3) Horwitz's interpretation requires that the Mallina Formation at Mons Cupri and Whim Creek is an intercalation within the Mons Cupri Volcanics because the felsic volcanics at Mons Cupri are at a lower stratigraphic position than those to the southwest. However, the southwestern volcanics are overlain by a 200 m slate and tuff unit a short distance to the north of Good Luck Well. This slate lithologically resembles the Rushall Slate and at one locality, 1 km to the west-northwest of the well, contains a basal conglomeratic rock (with rounded fragments of chert, falsic lava, quartzite and granite) similar to parts of the "Cistern formation".

Before closing this discussion it should be once more emphasized that a correlation of the Rushall Slate and the Mallina Formation would pose severe geochronological problems. Current geochronological data on the Mons Cupri Volcanics (de Laeter, pers. comm., Fitton and others, 1975, p. 10) indicates that its age falls within the range 2 700-2 330 m.y., or possibly even slightly younger. Thus, the Constantine Sandstone and the Mallina Formation, which on Horwitz's interpretation overlie the Mons Cupri Volcanics, could not be older than about 2 700 m.y. As noted previously, however, all available evidence indicates that both these formations are at least 3 000 m.y. old.

In conclusion, there would seem to be good grounds for rejecting the correlation of the Mallina Formation with the Rushall Slate. Because both the Lalla Rookh Sandstone and Constantine Sandstone are broadly conformable (local unconformities are present) with the underlying Cleaverville Formation across the Pilbara Block, they, and the overlying Mallina Formation, are placed in the Gorge Creek Group (as defined by Lipple, 1975).

Apart from a possible correlative of the Mons Cupri Volcanics 13 km northwest of Soanesville, the Whim Creek Group (as now defined) is confined to the Whim Creek Belt which lies to the south of the Caines Well Granite between the Balla Balla—Mount Negri area, and Warambie homestead. The total thickness of the succession ranges from 500 to 1 000 m, largely reflecting variations in the development of the Mons Cupri Volcanics. The Whim Creek Group unconformably overlies the Warrawoona Group 5 km west of Mount Fraser (Fitton and others, 1975, p. 15; Hickman, 1977d), and disconformably overlies the Mallina Formation 15 km southeast of Sherlock homestead (Hickman, 1977d). It unconformably overlies the Caines Well Granite at Mount Fraser and Mons Cupri, and is unconformably overlain by the Mount Roe Basalt (Fortescue Group) 3 km west-northwest of Warambie homestead.

The age of the Whim Creek Group may be estimated from geochronology by Dr J. R. de Laeter (pers. comm.). The group unconformably overlies the Caines Well Granite, which gives a metamorphic date of 2 700 m.y. and is intruded by rocks ranging in age from 2 500 to 2 330 m.y. The Mount Brown Rhyolite, considered by Dr. G. Sylvester (pers. comm.) to be intrusive, but by other workers (Miller, 1975; Miller and Gair, 1975) to be essentially extrusive and part of the Mons Cupri Volcanics, possesses a metamorphic age of 2 330 m.y. and an estimated primary age of 2 500 m.y. In summary, available isotopic evidence suggests that the Whim Creek Group is probably between 2 700 and 2 500 m.y. old.

Warambie Basalt

The basal formation of the Whim Creek Group is a vesicular and amygdaloidal basalt which Fitton and others (1975) named the Warambie Basalt. In the type area near Warambie homestead the formation is 200 m thick. About 3 km west-northwest of Warambie the unit dips southwards at 30° and is unconformably overlain by almost horizontally bedded Mount Roe Basalt. Eastwards from this locality the Warambie Basalt forms a narrow outcrop extending 40 km to Good Luck Well. Fitton and others (1975) indentified the formation 4 km south of Whim Creek where they stated that it is 100 m thick.

The composition of the Warambie Basalt ranges from basalt to andesite. The rock is locally porphyritic (plagioclase phenocrysts) and minor tuffaceous units occur near its base. At Mount Fraser a granite boulder conglomerate separates the Warambie Basalt from the Caines Well Granite. The boulders are well rounded, set in a basaltic matrix and measure up to 1 m in diameter.

Mons Cupri Volcanics

The Mons Cupri Volcanics (Fitton and others, 1975) crop out in an arcuate belt, up to 5 km wide, which follows the southern and eastern margins of the Caines Well Granite. In the type area at Mons Cupri, the formation is stated to attain a maximum thickness of about 700 m and is subdivided into a number of members:

	Rock Type	*Maximum Thickness (m)*
Top 4.	Tuff and sandy tuffaceous sedimentary rocks	30
3.	Felsic agglomerate, tuff and lava	550
2.	Mount Brown Rhyolite Member	200
Base 1.	Felsic volcanics and volcanoclastic sediments	220

The base of the Mons Cupri Volcanics is generally a tuffaceous unit and the top is a quartzofeldspathic tuff. According to Fitton and others (1975, p. 16), the lowest member is predominantly dacitic. The lava is fine grained, grey and contains amygdales filled with quartz, chlorite, and carbonate minerals. Feldspar-phyric dacite plugs have intruded this sequence and locally pass upwards into extrusive rocks such as lava and agglomerate. Miller and Gair (1975) referred to such felsic lava at Mons Cupri as the Mount Brown Rhyolite but Fitton and others reclassified it as the Mount Brown Rhyolite Member. It is a cream, massive rock, commonly spherulitic, and locally contains fragments of aphanitic felsic lava.

The Mount Brown Rhyolite Member is overlain by a sequence of felsic agglomerate containing thin intercalations of felsic lava and tuff. The agglomerate contains large (up to 1.5 m across) angular fragments of porphyry, felsic lava, basalt and granite and is economically important as the host rock to the Mons Cupri copper deposit. Above the agglomerate, finer pyroclastic rocks and partly reworked tuff generally occur at the top of the formation, but elsewhere the highest member is composed of well-sorted tuffaceous sandstone and minor conglomerate. Exposures of this conglomerate are accessible 2 km south of Whim Creek Hotel.

Miller and Gair (1975, p. 196) described the following five facies in the pyroclastic unit (informally referred to as the "Mons Cupri rhyolite fragmental") which overlies the Mount Brown Rhyolite Member: angular fragmented agglomerate; rounded fragmental rock (considered to be alluvial); coarse gritty tuff with rare rock fragments; massive sandy tuff; and stratified, probably waterlain, silty tuff. The upper member of the Mons Cupri Volcanics is informally named the "Cistern formation" (Miller and Gair, 1975, p. 197). Miller and Gair stated that it is a tabular unit and represents either a sill or a welded tuff. The possibility that it is a sill is suggested by their observation that its base contains fragments of the underlying pyroclastics and its top includes portions of the overlying slate formation (informally referred to as the "Whim Creek slate" but now named the Rushall Slate).

At Mons Cupri the upper part of the Mons Cupri Volcanics includes a 3-15 m thick unit of chert and tuff. Miller and Gair stated that this unit, which contains copper-lead-zinc-silver mineralization, caps a large chloritic pipe in which most of the copper ore at Mons Cupri is situated. The chert is a strictly local unit and appears to have no regional stratigraphic significance.

Additional petrographic features of the felsic rocks forming the Mons Cupri Volcanics are described in the section, "Felsic Volcanic Rocks", in Chapter 2.

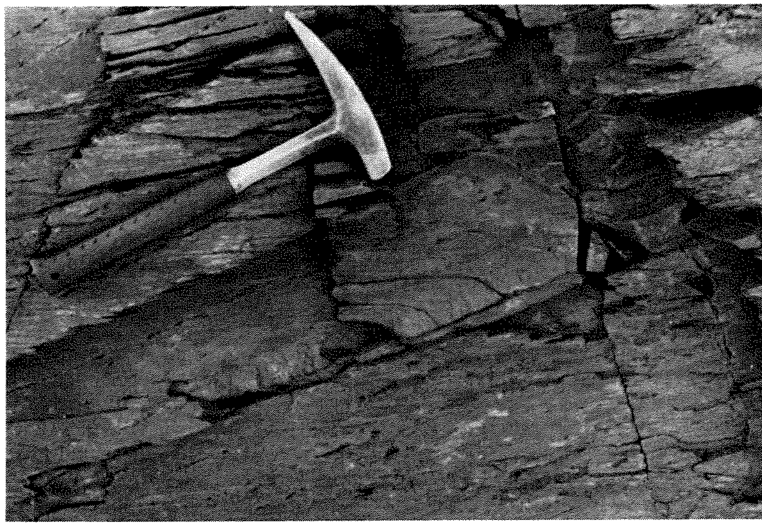
Rushall Slate

Previously informally referred to as the "Whim Creek slate", the unit is formally renamed the Rushall Slate and now defined for the first time.

The Rushall Slate derives its name from Rushall mine and crops out over 30 km^2 of country around Whim Creek mine (the type area) and northwards to the southern slopes of Mount Negri. Other areas where the formation is exposed are immediately southwest of Mons Cupri and near Good Luck Well, 8 km southeast of Sherlock homestead. Clastic sedimentary rocks cropping out to the north of Mount Negri and phyllitic sedimentary rocks west of Balla Balla are also correlated with this unit.

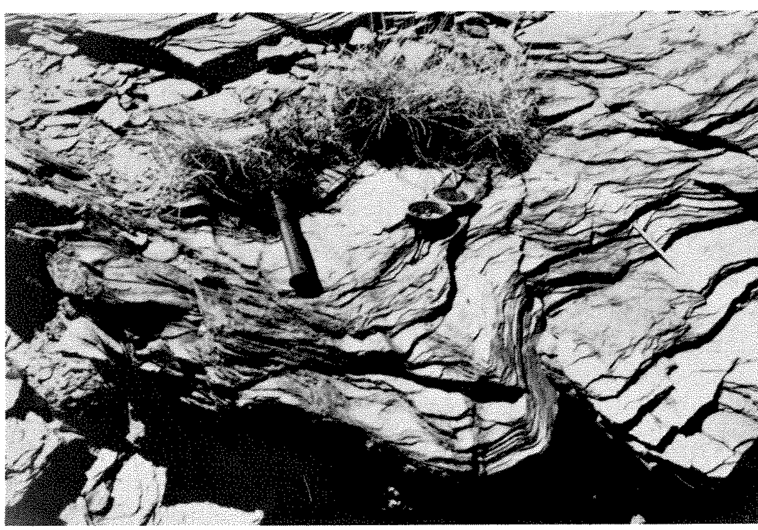
The Rushall Slate is approximately 200 m thick and consists of grey slate and phyllite, very subordinate flows of andesite and dacite, local beds of quartzite, and thin lenses of felsic tuff. At Mons Cupri a more important andesite unit (informally referred to as the "Comstock andesite" by Miller and Gair, 1975) occurs near the base of the formation and reaches a thickness of almost 70 m.

On surface exposures the most prominent foliation of the slate is a cleavage (Figs 23 and 24) related to northeast—trending folds in the Whim Creek Belt; a later, less conspicuous, crenulation cleavage strikes northwest (Hickman, 1977d). Bedding is easily discernible in drill core but outcrops of the formation generally require careful examination before their attitude can be clearly established. Graded bedding is common near the base of the slate south and southeast of Whim Creek and proves the succession to be right-way-up. According to Reynolds and others (1975, p. 193), the lower part of the Rushall Slate includes reworked tuffaceous material.



GSWA 19022

Figure 23. **Slaty cleavage in the Rushall Slate 1 km south of Whim Creek Hotel. Note cleavage refraction in a graded bed.**



GSWA 19023

Figure 24. **Outcrop of Rushall Slate 1 km southwest of Whim Creek Hotel. Slaty cleavage is folded by open crenulations.**

Miller and Gair (1975) suggested that the Rushall Slate was deposited in a caldera lake, the "Whim Creek slate basin". It should be noted, however, that although the formation accumulated in a volcanic environment, and possibly in small depositional basins restricted to the Sherlock-Whim Creek-Balla Balla area, the basin structure at Whim Creek must have formed after deposition because bedding in the slate is essentially parallel to the formation's basal contact. Thus, the boundaries of the present structural basin at Whim Creek should not be equated with those of a depositional basin.

At Mount Negri the Rushall Slate is unconformably overlain by the Negri Volcanics, and at Good Luck Well the formation is unconformably overlain by a sequence of basaltic and intermediate lava flows. Fitton and others (1975, Fig. 1) correlated the latter with the rocks at Mount Negri, but for reasons presented later the writer considers that they probably belong to a different stratigraphic unit (the Louden Volcanics). The succession at Good Luck Well is as follows:—

	Thickness (m)
Louden Volcanics	
Basalt	
............................low-angle unconformity	
Rushall Slate	
Shale, cleaved	50
Tuff, well-bedded, felsic to intermediate, water-lain; graded bedding and dacitic 'bombs'; some greywacke	50
Slate, with thin beds of fine-grained tuff and lava	100
....	
Mons Cupri Volcanics	
Dacitic lava, tuff and agglomerate	

About 1.5 km west of Mountain Well an unusual conglomeratic rock crops out (in poorly exposed ground) in a position which probably places it close to the base of the formation. Rounded clasts of chert, felsic lava, quartzite and granite up to 200 mm in diameter are set in a quartzite matrix. No bedding is visible but the rock appears to be a metasediment and may occupy a similar stratigraphic position to the conglomerate at the top of the Mons Cupri Volcanics 2 km south of Whim Creek Hotel.

OTHER FORMATIONS

The Louden Volcanics (new name) and the Negri Volcanics unconformably overlie the Whim Creek Group and appear to be separated by an unconformity. Fitton and others (1975) regarded both units as forming part of the Negri Volcanics.

Louden Volcanics

The Louden Volcanics are herein defined as a succession of intermediate, basaltic and ultramafic volcanic and intrusive rocks cropping out over 150 km^2 of country between Peawah Hill and Mountain Well. No type section can be designated because the formation is fault bounded in almost all parts of its outcrop. The type area is 6 km south-southwest of Mons Cupri, around the headwaters of Louden Creek. Good exposures are also available along the old route of the North West Coastal Highway east of Mount Negri. Hickman (1977d, Fig. 28) showed the boundaries of the formation but did not formally name it, referring to it as a unit of "quench-textured basalt, high-Mg basalt, gabbroic and peridotitic sills". Rocks of identical lithology to those at Louden Creek which occur east of the Sherlock River 10 km north of Kangan Pool, and between Mount Fraser and Warambie (Plate 1A), are correlated with the formation.

In the type area the unit includes the following rock types: pillow basalt; massive, aphanitic, mafic to intermediate lava; spinifex-textured harzburgite; and dolerite and gabbro; all dipping southeastwards at 50°. Outcrop width and a relatively consistent dip indicated a thickness of strata in excess of 2 000 m; both the upper and lower contacts are faults. Approximately 6 km east of the junction of the Sherlock River and the Little Sherlock River, flows of high-magnesium basalt (8.0-12.0 per cent MgO) with coarsely spinifex-textured tops are intercalated with pillowed lava of similar composition. The pillows also exhibit a fine-grained spinifex texture. In thin section (Fig 16) skeletal olivine (partly altered to serpentine) plates are set in a groundmass of feathery pyroxene (now amphibole). Some of the rocks contain acicular amphibole (after pyroxene) instead of serpentine, and large euhedral phenocrysts of pyroxene. Vesicles are scattered throughout and generally infilled by chlorite (less commonly quartz, epidote or calcite). Hallberg (1974, p.6) referred to the Louden Volcanics southeast of Sherlock homestead as an "unusual volcanic rock which consists of fresh, euhedral clinopyroxene phenocrysts, rare rounded and resorbed plagioclase phenocrysts and spherical amygdales up to 7 mm in diameter . . . set in a matrix of feathery amphibole". Hallberg stated that although these rocks texturally resemble high-magnesium basalt their chemistry is intermediate (4.01-5.23 per cent MgO, 3 samples). He suggested that the rocks he examined might represent the residue of the fractional crystallization of a more mafic magma. It appears that Hallberg sampled spinifex-textured andesites. Intermediate and silicified lava, which exhibits a quench texture, crops out over a considerable area of country to the north of the high-magnesium basalts, and between the latter and the Rushall Slate. Between the Sherlock River and Good Luck Well rocks correlated with the Louden Volcanics comprise the following units:

		Thickness (m)
South	7. High-magnesium basalt and pillow basalt with minor ultramafic and mafic sills.	1000
	6. Silicified intermediate lava	500
	5. Basaltic to andesitic agglomerate	20
	4. Slate	2
	3. Basalt	20
	2. Gabbro sill	0-30
North	1. Basalt.	0-20

——————————Unconformity——————————

It should be noted that a certain amount of doubt exists concerning the relationship between units 1-6 and unit 7; units 1-6 are gently inclined whereas unit 7 dips southwards at about 45°. The boundary in question is shown on Hickman's (1977d, Fig. 28) map of the Whim Creek area as a contact between "silicified and epidotized basalt" and "quench textured basalt, high-Mg basalt, gabbroic and peridotitic sills". The possibility that the boundary is an unconformity, or even a fault, cannot be discounted. At Warambie homestead, for example, the high-magnesium basalt unit is in direct contact with the Warambie Basalt; it appears to stratigraphically overlie it, however, since both units dip southwards at about 30°.

Northeast of Mount Negri the Louden Volcanics are inclined southwards and westwards at moderate angles. The Negri Volcanics are relatively horizontal and appear to unconformably overlie the quench-textured assemblage. Hallberg (1974, Table 3) presented analyses of two samples from a road cutting 8 km north of Whim Creek. The rocks are basaltic andesite or andesite on present chemical composition but their alumina content is abnormally low (about 11 per cent). It seems quite probable that the rocks are silicified, but if they were originally basalt their potash content is rather high (about 1.5 per cent)

In the Louden Creek area, the Negri Volcanics are separated from the Louden Volcanics by a major fault. On the northwest side of this fault, the Negri Volcanics dip gently northwestwards whereas on the southeast side the Louden Volcanics are inclined at about 50° southeastwards. Lithological differences between the two formations are noted in the description of the Negri Volcanics. The Louden Volcanics are unconformably overlain by the Mount Roe Basalt 5 km southeast of Mount Negri and west of Warambie homestead, and are consequently Archaean in age.

Negri Volcanics

The name "Negri Volcanics" was first used by Gair (1968) and eventually published by Fitton and others (1975, p. 18). The formation was also referred to by Miller and Gair (1975) as the "Mount Negri Volcanics" (informal name). Fitton and others (1975) described the formation as a suite of predominantly mafic to felsic lavas occurring north of Whim Creek and also in a 3-4 km wide belt running parallel to and south of the Mons Cupri Volcanics. The thickness of the formation was said to be 500-600 m and the dominant rock types were described as tholeiitic lavas ranging in composition from basalt to andesite. The authors included the Louden Volcanics (as now defined) within the formation.

The type area of the Negri Volcanics is Mount Negri where the unit consists of variolitic mafic to intermediate lava flows, almost flat lying, and unconformably overlying the Rushall Slate and the Mons Cupri Volcanics. Identical rocks crop out in a shallow synclinal structure 6 km southwest of Mons Cupri. In this area conglomerate occurs near the base of the Negri Volcanics, 3 km, southwest of Mons Cupri (Fitton and others, 1975, p. 18). Microscopic examination of the lava southwest of Mons Cupri reveals a fibrous groundmass of amphibole containing pyroxene phenocrysts and large ovoid masses of relatively undeformed material. The groundmass amphibole has a preferred orientation and field observations show this to be aligned to a steeply inclined cleavage. Fine-grained quench-like textures may be a product of metamorphism. The rock possesses a MgO content of about 6.0 per cent, but it shows effects of silicification.

From the above descriptions it will be obvious that the field appearances of the Louden Volcanics and the Negri Volcanics are different and that, whereas the Louden Volcanics are generally moderately to steeply inclined, the Negri Volcanics are fairly flat lying. For these reasons the two rock units are distinguished as discrete mappable formations separated by a discordant contact.

The age of the Negri Volcanics is presumed to be late Archaean because the rocks have been cleaved by deformation not affecting the Mount Roe Basalt. No stratigraphic contact exists between the Negri Volcanics (as now defined) and the Mount Roe Basalt.

CHAPTER 3

Proterozoic

Deformation and erosion of the Archaean rocks commenced early in the Pilbara Block's history but did not occur at the same time or on the same scale in all areas. Shortly after intrusion of the post-tectonic granites (2 700-2 600 m.y.) the surface of the area had been reduced to a terrain of undulating hills and valleys. In general, granitic rocks formed the uplands, and the valleys and basins were underlain by volcanic and sedimentary strata. A Lower Proterozoic succession of basaltic and andesitic volcanics with intercalated sedimentary rocks—the Fortescue Group—was deposited unconformably on this surface, the earlier formations being restricted to the basins but subsequent units encroaching progressively onto the granitic uplands. Conformably overlying the Fortescue Group is the Hamersley Group, a sequence of chert, banded iron-formation, shale, carbonate rocks and subordinate volcanics (Table 2).

These Lower Proterozoic strata (comprising part of the Mount Bruce Supergroup) are believed to have been deposited over the entire block but subsequent erosion has removed them from all areas except its southwestern, southern and eastern sides, and a small outlier to the west of Marble Bar.

Middle Proterozoic sedimentary rocks are included in Plate 1B, (See also Table 2), but discussion of these is limited. Proterozoic intrusions include granitic stocks, granophyre, porphyry sills, dolerite sills, felsic dykes and dolerite dykes.

STRATIGRAPHY

LOWER PROTEROZOIC

The Mount Bruce Supergroup (Halligan and Daniels, 1964) is composed of three groups: the Fortescue Group, Hamersley Group and Wyloo Group, in ascending stratigraphic order. The Wyloo Group does not crop out within the area covered by Plate 1, but formations of the other two units attain a combined maximum thickness of about 5 000 m Table 2).

FORTESCUE GROUP

About 2 600 m.y. ago, or slightly later, volcanic activity commenced across the area of the Pilbara Block. Basaltic and andesitic lava flows were poured onto the land surface during four main eruptive phases. These phases were separated by periods of volcanic quiescence in which sediments accumulated. The sedimentary rocks so formed include sandstone, conglomerate, limestone, shale and chert. This alternation of volcanic and sedimentary rock units facilitates stratigraphic subdivision of the Fortescue Group into a total of eight formations.

Top	Jeerinah Formation
	Maddina Basalt
	Kuruna Siltstone
	Nymerina Basalt
	Tumbiana Formation
	Kylena Basalt
	Hardey Sandstone
Base	Mount Roe Basalt

As originally defined (MacLeod and others, 1963), "the upper limit of the group is arbitrarily placed at the base of the Marra Mamba Iron Formation" (i.e. the top of the Jeerinah Formation). Kriewaldt (1964b) commented that on lithological grounds the boundary between the Fortescue and Hamersley Groups should be placed at the base of the Jeerinah Formation; the same point was made by Trendall and Blockley (1970, p.33). This bulletin retains the original definitions of the two groups, although any future detailed investigation of the succession may result in the position of the boundary being moved to the base of the Jeerinah Formation.

Trendall (1975a, p. 124) summarized the development of stratigraphic nomenclature in the Fortescue Group during the period 1962 to 1969. Because 1:250 000 scale mapping of the area within Plate 1 commenced in three separate areas (Marble Bar—Nullagine—Balfour Downs—Port Hedland; Mount Bruce; and Dampier at about the same time (1956 to 1962) it is not surprising that different stratigraphic subdivisions of the Fortescue Group resulted (Table 5). The differences between the east Pilbara subdivision (chiefly after Noldart and Wyatt, 1962) and the subdivisions of the other two areas were extremely difficult to reconcile. Since Trendall's account was written, the Geological Survey has remapped Marble Bar, Nullagine, Yarrie and Port Hedland with the result that the east Pilbara succession has now been successfully correlated with that previously established farther west. Plate 1B is the first published map to apply a single stratigraphic subdivision of the Fortescue Group to the entire area. This subdivision corresponds exactly to that on the four recently remapped 1:250 000 Sheets, and is very similar to that on all the other Sheets, except Balfour Downs. Balfour Downs has not been remapped and the new subdivision there is based on recent traverses and air photo interpretation. In the west Pilbara, Plate 1B differs from the published 1:250 000 sheets in distinguishing the Tumbiana Formation (previously included within the Pillingini Tuff).

Mount Roe Basalt

The Mount Roe Basalt (Kriewaldt, 1964b) is the lowest formation of the Fortescue Group. Varying in thickness from 0 to 500 m (Kriewaldt noted an exceptional thickness of 2 400 m at Mount Roe), the formation is composed chiefly of amygdaloidal, vesicular, glomeroporphyritic and columnar-jointed basalt and andesite. Basal, lenticular polymictic conglomerate units and sandstone separate the formation from the underlying Proterozoic—Archaean unconformity at numerous localities including Yandicoogina, Eastern Creek, Police Creek, Wallabirdee Ridge, Just-in-time, Glen Herring, Paddy Market Creek, Warralong Creek, Miralga Creek (10 km west of Cooke Bluff Hill and 8 km northeast of Little Shaw Well), Salgash, Kangan Pool (Sherlock River), Mount Ada to Mount Oscar, KAP 2 and Devil Creek.

TABLE 5. CORRELATION OF THE FORTESCUE GROUP BETWEEN VARIOUS AREAS

<table>
<tr><th>YARRALOOLA</th><th>PYRAMID</th><th colspan="2">MOUNT BRUCE</th><th colspan="2">ROY HILL</th><th>BALFOUR DOWNS</th><th>*NULLAGINE and MARBLE BAR</th><th rowspan="2">PILBARA BLOCK (This Bulletin)</th></tr>
<tr><th colspan="8">1:250 000 Sheets</th></tr>
<tr><td>JEERINAH FORMATION</td><td>JEERINAH FORMATION</td><td colspan="2">JEERINAH FORMATION</td><td colspan="2">JEERINAH FORMATION</td><td>LEWIN SHALE (lower part)</td><td>mapped as part of CARAWINE DOLOMITE and TUMBIANA PISOLITE</td><td>JEERINAH FORMATION</td></tr>
<tr><td>MADDINA VOLCANICS</td><td>MADDINA BASALT</td><td rowspan="5">MOUNT JOPE VOLCANICS</td><td>Bunjinah Pillow Lava Member</td><td rowspan="5">MOUNT JOPE VOLCANICS</td><td>Maddina Basalt Member</td><td rowspan="3">LITTLE DE GREY LAVA (in part)</td><td rowspan="3">"UPPER" LITTLE DE GREY LAVA</td><td>MADDINA BASALT</td></tr>
<tr><td rowspan="3">PILLINGINI TUFF</td><td rowspan="3">PILLINGINI TUFF</td><td rowspan="3">Pyradie Pyroclastic Member</td><td>Kuruna Silstone Member</td><td>KURUNA SILTSTONE</td></tr>
<tr><td>Nymerina Basalt Member</td><td>NYMERINA BASALT</td></tr>
<tr><td>Tumbiana Pisolite</td><td>TUMBIANA PISOLITE</td><td>TUMBIANA PISOLITE</td><td>TUMBIANA FORMATION</td></tr>
<tr><td>KYLENA VOLCANICS</td><td>KYLENA BASALT</td><td>Boongal Pillow Lava Member</td><td>Kylena Basalt Member</td><td>LITTLE DE GREY LAVA (in part)</td><td>"LOWER" LITTLE DE GREY LAVA and "UPPER" COONGAN VOLCANICS</td><td>KYLENA BASALT</td></tr>
<tr><td>CLIFF SPRINGS FORMATION</td><td>CLIFF SPRINGS FORMATION</td><td colspan="2">HARDEY SANDSTONE</td><td colspan="2">BEATONS CREEK CONGLOM-ERATE</td><td></td><td>GREEN HOLE CONGLOMERATE, GLEN HERRING SHALE, BEATONS CREEK CONGLOMERATE</td><td>HARDEY SANDSTONE</td></tr>
<tr><td>MOUNT ROE BASALT</td><td>MOUNT ROE BASALT</td><td colspan="2"></td><td colspan="2"></td><td></td><td>"LOWER" COONGAN VOLCANICS</td><td>MOUNT ROE BASALT</td></tr>
</table>

* Noldart and Wyatt (1962)

These basal arenaceous beds are of economic interest as potential sources of gold and uranium. Shale occurs at the base of the formation in some localities and near Granite Well a thin carbonate unit is exposed.

Agglomerate and tuff of intermediate to dacitic composition form thick lenticular units within the formation at Meentheena (Hickman, 1974), Twenty Ounce Gully (7 km south), Bamboo Creek, Helen Well, Granite Well (7 km southwest), Warambie, Mount Anketell, Dixon Island and Mount Roe.

A distinctive feature of the Mount Roe Basalt is the glomeroporphyritic texture commonly exhibited by its lava. Phenocrysts of plagioclase (generally sericitized) up to 10 mm long form clusters within a fine-grained, variably carbonatized groundmass.

The depositional environment of the Mount Roe Basalt is described by Kriewaldt (1964) as continental on a peneplain containing monadnock ridges of chert and jaspilite. Volcanism is said to have been accompanied by local subsidence, possibly along faults associated with fissure vents feeding the flows. Sediments within the formation are considered to be terrestial shallow-water deposits. In the east Pilbara some flows contain pillow structures (e.g. near Blue Bar mine) which indicates that deposition of the volcanic pile was locally subaqueous.

Hardey Sandstone

The Hardey Sandstone (MacLeod and others, 1963) conformably overlies the Mount Roe Basalt or, where the latter is absent, unconformably overlies Archaean rocks. The formation is composed chiefly of sandstone and conglomerate with minor intercalations of shale and tuffaceous sediment. In the west Pilbara the unit contains a high proportion of pyroclastic material and has previously been referred to as the Cliff Springs Formation (Kriewaldt and Ryan, 1967). Williams (1968) defined the Cliff Springs Formation as a predominantly tuffaceous unit containing subordinate clastic and, less commonly, calcareous rocks. Volcanic pisoliths are said to be present at several horizons.

In the east Pilbara it is now recognized that the Beatons Creek Conglomerate, Green Hole Conglomerate and Glen Herring Shale of Noldart and Wyatt (1962) are all part of the Hardey Sandstone. These units are now regarded as being members of the Hardey Sandstone and the names are valid only in the type areas.

Facies changes and thickness variations are important features of the Hardey Sandstone, which was deposited either in separate basins or possibly in a series of deep basins connected by shallow narrow depressions (valleys or straits).

An examination of local thickness variations does not support the relatively simple paralic interpretation of Horwitz and Smith (1978) and sedimentological and geochemical evidence (Hickman and de Laeter, 1977) indicate that deposition was initially continental.

About 20 km west of Nullagine the formation is 1 000 m thick and consists of coarse sandstone and beds of conglomerate passing upwards into wacke sandstone, tuffaceous beds, shale, mudstone and ooidal deposits. Beds of conglomerate are locally developed at the top of the formation but these are of variable thickness and thin out along strike. An intercalation of massive, columnar-jointed basalt, 0 to 30 m thick, is present in the upper part of the succession at Jim Well. In the Meentheena and

Bamboo Creek areas the lower part of the Hardey Sandstone consists of grey lithic and tuffaceous sandstone with intercalations of shale. This sequence passes upwards into a prominent grey shale overlain by a thick sequence of well-bedded sandstone containing beds of conglomerate. The top of the formation contains thin units of tuff, siltstone and mudstone. As near Nullagine, the total thickness of the Hardey Sandstone is about 1 000 m. Eastwards from Bamboo Creek the formation wedges out within a distance of 30 km, from which point the Kylena Basalt rests directly on the Mount Roe Basalt, probably disconformably. A similar stratigraphic attenuation occurs westwards from Bamboo Creek towards Marble Bar, Glen Herring and Warralong Creek. Within the 1 500 km^2 Proterozoic outlier preserved in this area the Hardey Sandstone is represented by 10 to 200 m of sandstone, conglomerate, tuff, siltstone shale and local basaltic lava flows. It is significant that the outlier is a structural basin positioned over a five-sided Archaean syncline (Plate 1B) and that the Hardey Sandstone is thickest around the headwaters of Warralong Creek, an area which includes the centres of both these structures. The inference is that the Proterozoic depositional basin was positioned within the Archaean syncline and that Proterozoic deformation essentially accentuated this structure.

Southwest of Warralong Creek the Hardey Sandstone reaches a thickness of approximately 200 m in smaller outliers near Soanesville. Here the succession consists of a 40 m thick basal conglomerate overlain by 5 m of pyritic siltstone and shale. The upper part of the formation exceeds 100 m and is composed chiefly of sandstone.

A sequence of well-bedded, cross-stratified quartzite, grit and conglomerate in a trough south of Leilera Creek is correlated with the Hardey Sandstone. The southern margin of the trough is faulted against Archaean chert and conglomerate, but the northern margin has a well-exposed angular unconformity over Archaean grit and sandstone. The sedimentary rocks are an interbedded sequence of quartzite, sandstone, grit, and conglomerate containing well-rounded clasts of vein quartz, massive and banded chert, sandstone and minor chlorite schist derived from the surrounding Archaean rocks. The total thickness of the succession at this locality is about 300 m.

Two elongate basins, about 4 km south of Soanesville mining centre, contain grit and conglomerate correlated with the Hardey Sandstone. The sequence unconformably overlies Archaean greenstones and is faulted in graben-like structures against Archaean chert. Well-bedded, locally cross-stratified grit is interbedded with conglomerate in which clasts include minor basalt and pyritic felsic volcanic rocks; ultramafic cobbles occur where basal conglomerate overlies Archaean ultramafic rocks. The probable thickness of the sequence is about 300 to 500 m.

In the west Pilbara the Hardey Sandstone crops out almost continuously for 220 km along the northern side of the Chichester Range. Within the Pyramid Sheet area conglomerate and sandstone in the lower part of the formation pass upwards into tuff and agglomerate. This upper pyroclastic unit is named the Lyre Creek Agglomerate Member (Kriewaldt and Ryan, 1967). The formation becomes thicker westwards and in the Cooya Pooya area the succession measures about 250 m. Farther west at Eramurra Creek on the Yarraloola Sheet it thins to about 6 m. Kriewaldt and Ryan (1967) suggested that Cooya Pooya is situated at, or near, a volcanic centre which discharged an exceptional thickness of pyroclastic material. Ryan (1966) assigned a 300 m thick sandstone unit at Mount Ada to the Hardey Sandstone, and this stratigraphic correlation is accepted. However, the writer's examination of sandstone north of the Mount Roe Basalt at this locality suggested that this sandstone unit was unconformably overlain by the Mount Roe Basalt. On Plate 1B the northern unit is tentatively correlated with the Lalla Rookh Sandstone.

Kylena Basalt

The Kylena Basalt (MacLeod and de la Hunty, 1966) conformably overlies the Hardey Sandstone or, where the latter is absent, unconformably overlies Archaean rocks (generally granitic). In the Gregory Range the formation overlies conformably or disconformably the Koongaling Volcanics (a felsic equivalent of the Mount Roe Basalt). Ranging in thickness up to 500 m, the Kylena Basalt consists of dark grey to grey-green massive, amygdaloidal and vesicular basalt and andesite. Pillow structures are locally developed and many of the flows are columnar jointed. Agglomerate occurs in the lower part of the formation in Glen Herring, at Coolbanacoula Pool (30 km west of Nullagine), Copper Creek (Meentheena area), Green Hole and Pear Creek. Felsic and intermediate lava occurs in the upper part of the formation near Bonnie Pool, Mount Ian Well, Hay Creek and numerous areas in the West Pilbara, including Eramurra Creek. Recent investigations by various Survey geologists have suggested that the formation may be predominantly andesitic to dacitic in the west Pilbara rather than basaltic to andesitic as in the east.

Although the Kylena Basalt is chiefly a volcanic formation, sedimentary beds are widespread. Siliceous limestone units, generally no more than 2 or 3 m thick occur at various levels throughout the Pilbara, and pisolitic tuff is also present. In the Warralong Creek outlier the Kylena Basalt contains exceptionally thick sandstone members. It appears that in this area conditions of deposition which gave rise to the Hardey Sandstone recurred during extrusion of the lava sequence. Black shale and tuff form minor parts of the Kylena Basalt in the Isabella Range.

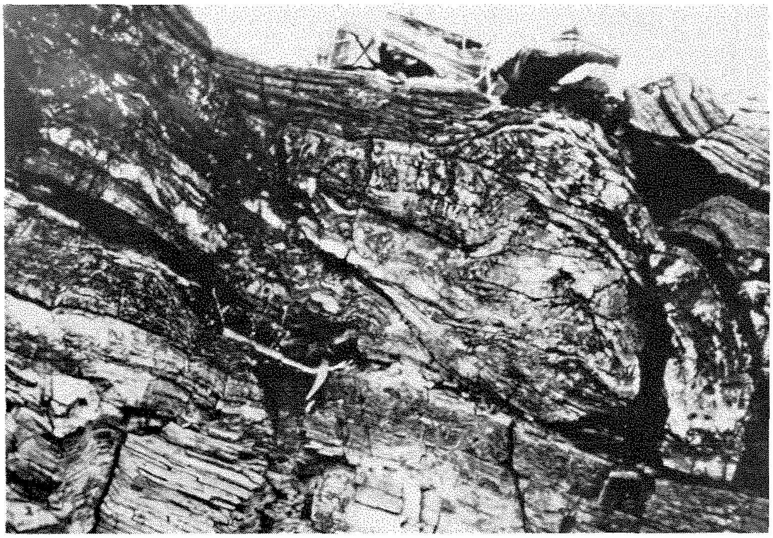
Tumbiana Formation

The Tumbiana Formation ("Tumbiana Pisolite", Noldart and Wyatt, 1962; renamed by Hickman and Lipple, 1975) comprises two members, the Mingah Tuff Member and the Meentheena Carbonate Member (each formally defined by Lipple, 1975).

The Mingah Tuff Member forms the lower half of the Tumbiana Formation and is composed of pisolitic tuff with local units of agglomerate, basalt and beds of sandstone, siltstone and ripple-bedded limestone (as developed in the overlying carbonate member). Ripple marks, cross-bedding and washout structures are preserved in the sediments, and pisolitic beds are commonly graded. Trendall (1965a) discussed the origin of pisolitic tuff. In the type area around Pelican Pool the Mingah Tuff Member is 150 m thick and the unit maintains this general thickness over the greater part of its outcrop from the Gregory Range to Cape Preston.

The Meentheena Carbonate Member is generally 10 to 50 m thick and consists of ripple-bedded siliceous limestone containing thin beds of tuff and shale. Apart from ripple marks the member contains syndepositional slump structures (Fig. 25) and algal stromatolites identified as *Gruneria* and *Alcheringa narrina*. Excellent exposures of stromatolites are available on the banks of the Nullagine River between

Pelican Pool and Meentheena. Other accessible fossil localities occur on the northern scarp of the Chichester Range at Mount Herbert and on the Port Hedland-Wittenoom road.



GSWA 19024

Figure 25. Slump structure in the Meentheena Carbonate Member, west bank of Nullagine River, Meentheena.

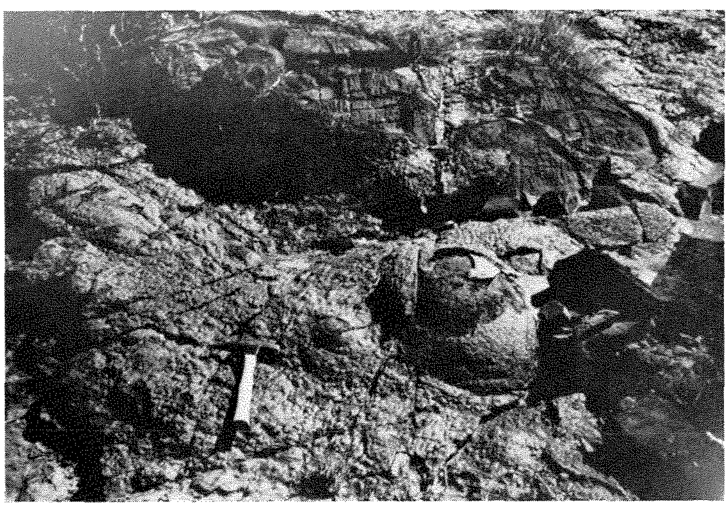


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Figure 26. Small cumulate and columnar stromatolites forming domes in the Meentheena Carbonate Member, west bank of Nullagine River, Meentheena.

The Tumbiana Formation is not fully developed in all parts of its outcrop. At Cape Preston the formation is represented chiefly by limestone, whereas in the Gregory Range either the tuff or the limestone member may be locally absent. Similar variations are also encountered in intervening areas, but in general the succession is remarkably constant.

Nymerina Basalt

Generally between 100 and 300 m thick, the Nymerina Basalt (MacLeod and de la Hunty, 1966) conformably overlies the Tumbiana Formation in the east Pilbara. Plate 1B shows that the formation wedges out westwards between Hooley homestead and Nunyerry mine. MacLeod and de la Hunty (1966) stated that in the Roy Hill Sheet area the "Nymerina Basalt Member" (subsequently upgraded to formation by Hickman and Lipple, 1975) "consists of dark-green vesicular and amygdaloidal basalt with some pillow lava bands, interbedded pyroclastics and sediments". The sediments are said to include limestone, siltstone and pisolite. Mapping on Marble Bar, Nullagine and Yarrie (1972 to 1974) has established that the formation extends northeastwards to Warrawagine. Outside the Roy Hill area pyroclastic rocks are uncommon. Apart from the type of lava mentioned above, the Nymerina Basalt is composed of a distinctive coarse-textured basalt. This rock occurs in thick massive flows and consists of interlocking oligoclase laths (up to 2 mm long) and glomeroporphyritic clinopyroxene phenocrysts set in a fine basaltic groundmass.

Thin tuff units are present in the lower part of the formation between White Springs and Hooley, and tuff has been noted near Boodalyerrie Creek and Bookabunna Well. Felsic lava forms a very minor part of the formation near Boodalyerrie Creek.

Although it is known that the Nymerina Basalt thins from 300 m in the central part of the Nullagine Sheet to less than 50 m on the western part of Roy Hill (MacLeod and de la Hunty, 1966, p. 11) and near Eera Baranna Pool (Hickman and Lipple, 1975) the actual locality where it wedges out has not been pinpointed on the ground. The position of lateral termination shown on Plate 1B is based on air photo interpretation. Kriewaldt and Ryan (1967, p. 16) commented that lava which they mapped in the upper part of the Pillingini Tuff (correlated with the Tumbiana Formation, the Nymerina Basalt and the Kuruna Siltstone) near Hooley is correlated with the Nymerina Basalt, but they did not distinguish this formation on their map. Lava is not shown farther west within the Pillingini Tuff. Throughout the east Pilbara the Nymerina Basalt is separated from the overlying Maddina Basalt by a thin intervening sedimentary formation, the Kuruna Siltstone. It is the presence of this unit which has permitted the recent air photo interpretation near Hooley.

Kuruna Siltstone

As noted above, the Kuruna Siltstone (MacLeod and de la Hunty, 1966) is chiefly of significance as a marker unit between the upper two basalt formations of the Fortescue Group. The formation consists of sandstone and siltstone with local shale, ooidal sediments, pisolitic tuff and banded siliceous limestone. Its maximum thickness is 20 m and the distribution of the unit is limited to certain parts of the east Pilbara. Where the formation is absent, as in the Gregory Range, between Boodalyerrie Creek and Hays Creek, and on the Balfour Downs Sheet area, it is impossible to draw an accurate boundary between the Nymerina Basalt and the Maddina Basalt. In the Gregory Range the two basalt formations have been mapped as one unit, the Pearana Basalt.

Maddina Basalt

The Maddina Basalt (MacLeod and de la Hunty, 1966) consists of dark grey-green vesicular and amygdaloidal basalt and andesite. Williams (1968) noted an increasing development of felsic lava from east to west across the Yarraloola Sheet. Farther east felsic lava is commonly present close to the top of the formation.

In the east Pilbara the Maddina Basalt is generally between 100 m and 200 m thick, but the formation thickens to 600 m across the west Pilbara (Kriewaldt and Ryan, 1967; Williams, 1968). A feature of the Maddina Basalt, not so prominent in other basalt formations, is the widespread occurence of large amygdales and vugs. Well-formed quartz crystals line the vugs, and the amygdales (which according to Kriewaldt and Ryan (1967) locally measure up to 0.6 m in diameter) contain agate, calcite, quartz and other secondary minerals.

Jeerinah Formation

The Jeerinah Formation (MacLeod and others, 1963) conformably overlies the Maddina Basalt throughout the area represented on Plate 1. The formation is composed of sandstone, siltstone, shale and chert with local units of felsic lava, tuff and agglomerate, minor basalt and widespread dolerite sills. Its thickness ranges from about 150 m in the west Pilbara to almost 500 m in the east. Part of this discrepancy results from the eastern succession (Lewin Shale) including strata laterally equivalent to an iron-formation (Marra Mamba Iron Formation) which overlies the Jeerinah Formation in the west.

TABLE 6 GENERALIZED CORRELATION BETWEEN THE JEERINAH FORMATION AND THE LEWIN SHALE

	Yarraloola succession			Nullagine-Yarrie succession			
	Formation or Member		Thickness	Formation or Member			Thickness
HAMERSLEY GROUP	Marra Mamba Iron Formation		180 m		Shale and local BIF		10 m
FORTESCUE GROUP	Jeerinah Formation	Roy Hill Shale Member	35 m	Lewin Shale	Shale, chert and siltstone		200 m
	Jeerinah Formation	Nallanaring Volcanic Member	60 m	Lewin Shale	Baramine Volcanic Member	Volcanics	230 m
	Jeerinah Formation	Warrie Member	60 m	Lewin Shale	Baramine Volcanic Member	Shale, chert and dolomite	20 m
	Jeerinah Formation	Woodiana Sandstone Member	25 m	Lewin Shale	Local sandstone		20 m

The Woodiana Sandstone Member (MacLeod and de la Hunty, 1966) conformably or disconformably overlies the Maddina Basalt throughout the west Pilbara but in the east Pilbara is only well developed on Roy Hill and around Coonabunna Creek. The Warrie Member is predominantly shale with subordinate banded chert, jaspilite and mudstone. Carbonaceous and black at depth, the shale forms white outcrops; small pyrite concretions are commonly present, oxidized to limonite in surface exposures. Felsic agglomerate, tuff and lava units which make up the lower half of the Lewin Shale east of Warrawagine are collectively referred to as the Baramine Volcanic Member (Hickman and Chin, 1977). A basal unit of shale, banded chert and dolomite is probably equivalent to the Warrie Member. Southwards and southwestwards from the Baramine area the felsic volcanics are replaced by vesicular andesite and basalt. Volcanics are absent from the Lewin Shale and the Jeerinah Formation across much of the Pilbara but reappear in the Yarraloola Sheet area. Here, Williams (1968) stated that the Nallanaring Volcanic Member consists of aphanitic and spherulitic felsic lava and felsic pyroclastics overlain by pillowed basaltic lava. The Roy Hill Shale Member (MacLeod and de la Hunty, 1966) is lithologically indistinguishable from the Warrie Shale. Where the Nallanaring Volcanic Member is absent the two units are separated by beds of dolomite.

Koongaling Volcanics and Pearana Basalt

The eastern side of the Gregory Range from Binbianna Rock Hole to Snell Well contains a 1 000 m-thick succession of felsic volcanic rocks named the Koongaling Volcanics (Hickman, 1975a). Rhyolite and dacite lava flows predominate but there are local thick units of agglomerate and tuff. The formation is inclined westwards at about 10° and underlies the Kylena Basalt, aparently conformably. For this reason it is correlated with the Mount Roe Basalt. The Hardey Sandstone, which normally intercedes between the Mount Roe Basalt and the Kylena Basalt, is absent in the Gregory Range, although thin beds of tuffaceous sediment occur at the top of the Koongaling Volcanics in the Isabella Range.

The Pearana Basalt (Hickman, 1975a), also restricted to the Gregory Range, conformably overlies the Tumbiana Formation and conformably underlies the Jeerinah Formation (Lewin Shale). It is directly correlated with the Nymerina and Maddina Basalts, which cannot be distinguished in the Gregory Range because the Kuruna Siltstone is absent. Coarse-textured basalt of Nymerina type forms much of the lower part of the formation whereas vesicular, and locally glomeroporphyritic, basalt and andesite is characteristic of its upper half. Felsic and intermediate lava occurs near the top of the formation (cf. Maddina Basalt).

HAMERSLEY GROUP

The Hamersley Group (MacLeod and others, 1963) conformably overlies the Fortescue Group. It is approximately 2 500 m thick and, except for one of its eight constituent formations, is composed entirely of sedimentary rocks, chiefly BIF and shale.

Top	Boolgeeda Iron Formation
	Woongarra Volcanics
	Weeli Wolli Formation
	Brockman Iron Formation
	Mount McRae Shale
	Mount Sylvia Formation
	Wittenoom Dolomite (=Carawine Dolomite)
Base	Marra Mamba Iron Formation

In the east Pilbara the group is represented by only the Carawine Dolomite, but the Marra Mamba Iron Formation is present west of long. 119° 30′E. Other formations of the Hamersley Group occur only in the extreme western part of the area covered by Plate 1 B. Because so little of the Hamersley Group is exposed in the area under discussion its description here is brief.

Marra Mamba Iron Formation

In the west Pilbara and west of Roy Hill homestead the Jeerinah Formation is conformably overlain by the Marra Mamba Iron Formation (MacLeod and others, 1963). The formation consists of stilpnomelane shale, chert and BIF and, within the area of Plate 1 B, ranges in thickness from 20 to 150 m. The chert units have a characteristic yellow or yellow-brown colouring in most exposures, resulting from the breakdown of minnesotaite. Pinch and swell structures are common in the ferruginous beds.

In the east Pilbara, de la Hunty (1964) described jaspilite in the Lewin Shale 3 km southwest of Sunday Hill, and BIF units up to about 2 m in thickness have been noted in Carawine Gorge (Hickman, 1975a). In most areas northeast of Roy Hill, however, the Marra Mamba Iron Formation is absent from the succession.

Carawine Dolomite

The Carawine Dolomite (Carawine Dolomite Series, Maitland, 1919) is referred to as the Wittenoom Dolomite (MacLeod and others, 1963) in the Hamersley Range and west Pilbara areas. The name "Carawine Dolomite" is retained here because it has historical priority. Another reason for retaining the original name in preference to the one used farther west is that within the area under discussion the greater part of its outcrop occurs in the east Pilbara.

The Carawine Dolomite conformably overlies the Lewin Shale in the east Pilbara and the Marra Mamba Iron Formation in the west. Ranging in thickness up to 200 m, the formation consists of brown-weathered, well-bedded grey dolomite, with minor chert beds and veins generally less than 100 mm thick. In most exposures bedding is difficult to recognize but some sections are finely laminated. Shale intercalations are present in the upper part of the Carawine Dolomite between Roy Hill and Millstream (MacLeod and de la Hunty, 1966; Kriewaldt and Ryan, 1967). Where fresh, the dolomite is finely crystalline and grey-pink with faint colour banding. It contains sedimentary structures such as cross-beds and slumps, and diagenetic features such as styolites and chert nodules. Algal structures have been recognized at Woodie Woodie (de la Hunty, 1963, p. 31), but there is some doubt as to whether these occur in the Carawine Dolomite or the Waltha Woora Formation. The locality cited by de la Hunty is situated 8 km northeast of Tooncoonaragee Pool at lat. 21° 04′S, long. 121° 12′E. Stromatolites also occur 5 km southwest of Baramine.

In most areas, the Carawine Dolomite is poorly exposed, but its presence can generally be inferred from its topographic expression of broad valleys filled by scree and alluvium and walled by ridges of Lewin Shale or the Marra Mamba and Brockman Iron Formations. The main extent of the Oakover Valley coincides with the outcrop of the Carawine Dolomite, and the formation underlies the greater part of the Fortescue Valley.

Mount Sylvia Formation and Mount McRae Shale

Although widespread in the Hamersley Ranges, where they are described by MacLeod and others (1963) and subsequent workers (e.g. Trendall and Blockley, 1970), the Mount Sylvia Formation and the Mount McRae Shale are restricted to the Point James area of Plate 1 B. Even here exposures are poor and Williams (1968) does not separate the two formations in this part of the Yarraloola 1:250 000 Sheet. Elsewhere on the Yarraloola Sheet area the Mount Sylvia Formation consist of 25 m of shale containing three thin BIF members. The Mount McRae Shale is 35 m thick and predominantly composed of white-weathered, siliceous and dolomitic shale with interbedded chert; chert is said to increase in importance towards the northwest.

Brockman Iron Formation

The Brockman Iron Formation (MacLeod and others, 1963) is well exposed at Point James and north of Balmoral homestead. In the Hamersley Range the Bockman Iron Formation is over 600 m thick and contains four members: in ascending order these are the Dales Gorge Member, the Whaleback Shale Member, the Joffre Member and the Yandicoogina Shale Member. Only the lower two members are exposed at Point James where the Dales Gorge Member is 150 m thick.

The Dales Gorge Member is composed of seventeen BIF units, ranging in thickness from 2 to 15 m, separated by sixteen thinner units of shale containing minor chert and siderite. Although the type section of the member is situated in Wittenoom Gorge, some 270 km from Point James, the successions of the two areas are virtually indentical except that the Point James sequence is abnormally thick and contains slump structures. Readers are referred to Trendall and Blockley (1970, p. 41) for further description.

The Whaleback Shale Member consists of shale with subordinate chert and carbonate beds. Only the lower part of the unit is exposed at Point James.

Weeli Wolli Formation

The Weeli Wolli Formation (MacLeod and others, 1963), consists of BIF, shale and dolerite sills. Although not exposed, the formation is thought to underlie superficial deposits southwest of Point James.

MIDDLE PROTEROZOIC

Sedimentary rocks considered to be of Middle Proterozoic age (Table 2) are confined to the eastern and southeastern parts of the area.

ROCKS OF UNCERTAIN STRATIGRAPHIC AFFINITY

Pinjian Chert Breccia

The Pinjian Chert Breccia (Noldart and Wyatt, 1962) is a residual and replacement deposit unconformably overlying the Carawine Dolomite. Angular chert fragments are cemented by a cherty matrix locally rich in manganese and iron oxides.

Shortly after deposition of the Carawine Dolomite, which is presumed to have taken place in a shallow shelf sea or basin environment, emergence appears to have occurred in the area between Roy Hill and Warrawagine. Formations which farther southwest and west conformably overlie the Carawine Dolomite are absent in this area, due either to erosion or non-deposition. Because no relics of these units are preserved the latter explanation seems more probable. Normal processes of weathering resulted in the development of a karst topography, chert debris from the dissolved carbonate beds accumulating in the crevices. At some localities vertical dyke-like structures of chert breccia are surrounded by dolomite. A doline (sinkhole) occurs 5 km west of Ripon Hills mining centre and collapse structures in the Pinjian Chert Breccia are visible on air photographs of Upper Carawine Gorge.

The formation ranges in thickness up to 100 m and is unconformably overlain by the Waltha Woora Formation at Ripon Hills, 5 km west of Ragged Hills and in Wandy Wandy Creek, 7 km east of Two Sisters. Where unconformities with overlying Middle Proterozoic or Permian formations are not preserved, it is difficult to distinguish the Pinjian Chert Breccia from Tertiary cap rock.

Waltha Woora Formation

The Waltha Woora Formation (Noldart and Wyatt, 1962) consists of shale, siltstone, sandstone, dolomite and an impersistent basal conglomerate. The finer grained sediments are commonly tinged purple, and are locally manganiferous. Rapid vertical alternations of rock type are present and details of the unit's succession are imprecisely known. Algal bioherms of an as yet unidentified type of stromatolite (Figs. 27A and B), at least 10 m thick and up to several kilometres long, occur between Woodie Woodie and Mount Sydney.

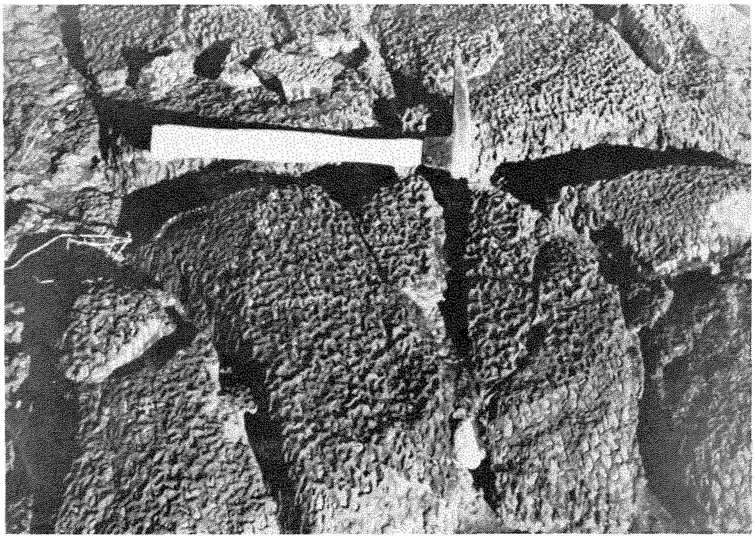
The formation crops out at Ripon Hills where the following general succession exists (thicknesses are approximate):

Top	5. Dolerite sill	30 m
	4. Sandstone	50 m
	3. Shale and siltstone	50 m
	2. Sandstone and grit. Structures resembling fossils	50 m
Base	1. Congolmerate and local ferruginous grit and breccia	10 m

——— Unconformity ———

Pinjian Chert Breccia

The basal conglomerate contains sub-rounded pebbles of chert within a quartzite matrix. Ferruginous grit crops out 3 km southwest of Mount Ian, but the origin of the iron is uncertain. Vertical columnar structures are present in unit 2 about 3 km north of Mount Ian. Field appearance suggests that these structures might be of organic origin (possibly worm burrows), but laboratory examination has provided no evidence to support this interpretation; the structures can be classified only as *fossilum problematicum* (Cockbain, 1974).



GSWA 19026

Figure 27A. **Columnar stromatolite (unnamed) from the Waltha Woora Formation 8 km southwest of Mount Sydney. View from above**

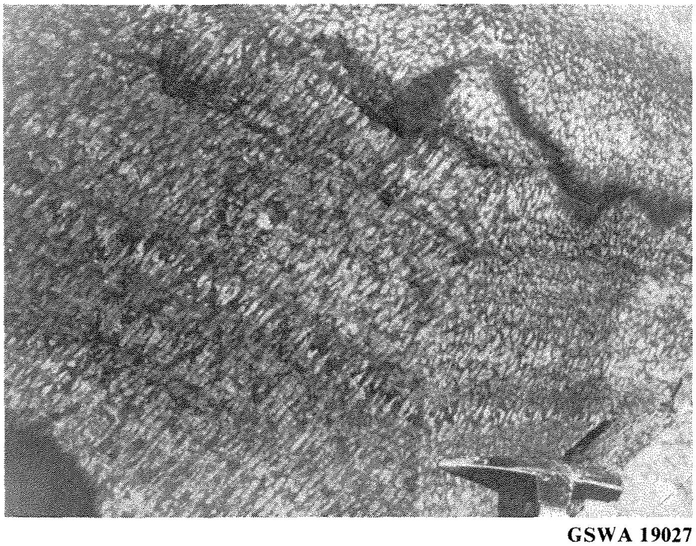


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Figure 27B. **As above, showing a vertical section across bedding.**

On Wandy Wandy Creek the Waltha Woora Formation possesses a 2 m thick basal conglomerate which unconformably overlies both the Pinjian Chert Breccia and the Carawine Dolomite. The conglomerate contains rounded to subrounded pebbles of quartz, chert and chert-breccia.

Determination of the stratigraphic relationship between the Waltha Woora Formation and the Manganese Subgroup, Bangemall Group and Yeneena Group is impeded by the absence of contacts in the Mount Sydney-Woodie Woodie area. Rather insubstantial evidence occurs 8 km southwest of Binbianna Rock Hole where shale and siltstone of identical lithology to the Waltha Woora Formation unconformably overlie the Carawine Dolomite and conformably, or disconformably underlie a sandstone-shale succession correlated with the Yeneena Group (Plate 1B; see also Williams and others, 1976, Fig. 42). If the shale-siltstone unit at this locality is part of the Waltha Woora Formation then the latter is either older than or belongs to the Yeneena Group. It may be significant that at Ripon Hills and Mount Sydney a pelitic lower part of the Waltha Woora Formation is overlain by sandstone and quartzite similar to that forming the basal formation of the Yeneena Group. The writer (Hickman, 1975a) previously suggested a correlation between the Waltha Woora Formation and the Manganese Subgroup (see also de la Hunty, 1963, p. 29), but recognition of an unconformity between the Bangemall Group (thought to include the Manganese Subgroup) and the underlying Yeneena Group (Williams and others, 1976) coupled with the above observations, now casts considerable doubt on that interpretation.

Eel Creek Formation

The Eel Creek Formation (Hickman and Chin, 1977) is a 475 m thick succession of dark grey shale containing intercalations of sandstone and conglomerate. The formation is restricted to the area around the headwaters of Eel Creek, 20 km east of Shay Gap, where the following succession is present:

Top	Quartz sandstone with rare shale	125 m
	Dark grey shale, minor siltstone, sandstone and several dolerite sills	300 m
Base	Hematite conglomerate and ferruginous sandstone	50 m

——————Unconformity——————

Archaean BIF and ferruginous sediments

The formation is unconformably overlain by Permian rocks and appears to overlie (exposure is poor) basaltic to andesitic rocks considered to belong to the Fortescue Group (Hickman and Chin, 1977). Its geographic isolation from strata known to be of Proterozoic age and the present lack of palaeontological or geochronological evidence requires any correlations made to be on purely lithological grounds. On the basis of lithology three possible correlations have to be considered: Hardey Sandstone; Waltha Woora Formation; Yeneena Group. The Hardey Sandstone does not possess any thick units of dark grey shale or dolerite sills and the lower part of the Yeneena Group is predominantly composed of sandstone. The most probable correlation would appear to be with the Waltha Woora Formation. It will be noted that there are certain broad similarities in the successions of the two units, i.e. basal ferruginous beds and an upper sandstone unit. At Ripon Hills the Waltha Woora Formation is also intruded by dolerite. More detailed stratigraphic studies must be undertaken, however, before the two formations can be correlated with any real confidence.

YENEENA GROUP

The Yeneena Group (Williams and others, 1976) crops out only along the eastern margin of the area covered by Plate 1B. It is essentially a shelf sequence of sandstone, shale and carbonate rocks and exceeds 5 000 m in thickness. Its age is provisionally estimated to be between 1 500 m.y. (approximate age of metamorphism in the Rudall Metamorphic Complex which unconformably underlies the group) and 1 100 m.y. (age of the Bangemall Group, unconformably overlying the Yeneena Group). Further stratigraphic information may be obtained from Chin and Hickman (1977) and Chin and others (1979).

BANGEMALL GROUP

The Bangemall Group (Halligan and Daniels, 1964) is an 8 000 m thick succession of alternating shale, sandstone and carbonate rocks with minor wacke, chert and conglomerate, and rare felsic lava. A detailed account of the group is provided by Muhling and Brakel (in press). Muhling and Brakel correlate the Manganese Subgroup (Manganese Group of de la Hunty, 1963) with the Backdoor Formation of the Bangemall Group.

The Manganese Subgroup crops out in the southeastern part of the area. It consists of shale and sandstone with local basal conglomerate and is approximately 500 m thick. Large dolerite sills intrude the unit around the headwaters of the Davis River.

ROCKS OF MINOR INTRUSIONS

Proterozoic minor intrusions include dykes and sills of dolerite and gabbro, felsic dykes, stocks of adamellite and sills of granophyre and dacite porphyry.

DOLERITE AND GABBRO DYKES

Dykes, ranging in composition from dolerite to gabbro, and locally quartz diorite, intrude the Archaean batholiths and greenstone belts and the Proterozoic succession. Variations in trend, cross-cutting relationships and stratigraphic relationships have been used to establish that several phases of Proterozoic dyke intrusion are represented.

In the Yule Batholith, contaminated xenolithic dykes with an east-northeast trend (Mundine Well Suite) mutually interfere with a suite of west-northwest trending dolerite dykes (Round Hummock Suite). Because of variable contamination the former dykes show a compositional range from dolerite to dacite and contain abundant quartz xenocrysts and remelted granitic xenoliths in an originally basaltic matrix.

The granitic country rocks adjacent to the dykes exhibit partial melting and metamorphism, generally extending for a distance equivalent to about half the width of the dyke. The affected zones often form parallel ridges with a slightly lower median strip due to the greater susceptibility to weathering of the dyke. Examples of the xenolithic dykes occur 8 km south from Spear Hill and 8 km northwest from Abydos homestead. The Mundine Well suite intrudes all formations of the Fortescue Group in the White Springs-Hooley area, and 30 km east of Millstream a 120 km long dyke with this orientation intrudes the lower part of the Hamersley Group.

Extensive, thick, medium-to-coarse-grained dolerite dykes trending in a north-northeast direction and forming prominent dark ridges, particularly on the batholiths, constitute the Black Range Suite. Although these dykes intrude the greenstone sequence, they are less persistent in the latter, and crop out only in an intermittent en echelon fashion. The best example is the Black Range dyke (Fig. 28) which has a total length of over 100 km and is up to 150 m wide. The dolerite has remelted the granitic country rock within 3 m of the contact and has a metamorphic aureole extending for about 70 m from the contact. The centre of the dyke is a normal coarse-grained dolerite except for a larger proportion of interstitial micropegmatite. The marginal dolerite and remelted granite show hybridization. Contamination of the fine-grained basalt margin is indicated by quartz xenocrysts, occasional oligoclase xenocrysts and from chemical analysis (Lewis and others, 1975).

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Figure 28. The Black Range dolerite dyke near Hillside. Photo by T. Blatchford

Lewis and others dated the Black Range dyke at 2 329 ± 89 m.y. (recalculated to 2 280 ± 87 m.y.), commented on its chemical composition and discussed its effects on adjacent country rock. The Cajuput dyke near Nullagine, extends north-northeastwards from Bonney Downs homestead (8 km northeast) to Dewhurst Well, a distance of 30 km. About 10 km to the north of Dewhurst Well a similar dyke, considered to be either an en echelon fissure or possibly the same structure connected at depth, extends north-northeastwards for a further 32 km. In some sections the Cajuput dyke attains a width of almost 1 000 m. South of Nullagine it is unconformably overlain by the Hardey Sandstone and contains partially assimilated xenoliths of the Mosquito Creek Formation. Hickman (1975a) points out that in the McPhee Creek area the northern branch of the dyke penetrates basaltic lava correlated with the Mount Roe Basalt, but it is not certain that this is an intrusive relationship; the basalt may be draped around the dyke. Moreover, although Proterozoic lava unconformably overlies Archaean felsic lava in the Doherty area, much of the basaltic lava immediately adjacent to the northern end of the dyke may be Archaean.

The Cajuput and Black Range dykes are lithologically and palaeomagnetically (Embleton, 1978) very similar. Intrusive relations indicate that the Black Range Suite is older than the Mundine Well and Round Hummock Suites and it probably represents the earliest phase of Proterozoic dyke intrusion. Such intrusions must have been feeders to the basaltic lava flows of the Fortescue Group. The age of 2 280 m.y. computed for the Black Range dyke clashes with the age of 2 600 m.y. computed for the Hardey Sandstone (Hickman and de Laeter, 1977). Preliminary geochronology on the Cajuput Dyke (Trendall, pers. comm.) indicates an age appreciably older than 2 280 m.y.; and it is questionable whether the Black Range result accurately reflects the true age of dyke emplacement. The Black Range date is based both on isotopic ratios of the dolerite and on those of partly remelted grantitic rocks within 6 m of its margin; the slope and error limits of the resulting isochron are heavily dependant upon the isotopic composition of the granites.

East-trending dolerite dykes intrude the southern part of the Corunna Downs Batholith. Fractures on the same trend as the dykes occur in the Hardey Sandstone 10 km to the east. The east-west dykes cut and displace the Black Range Suite, but their age relationships to the Mundine Well and Round Hummock Suites are uncertain.

DOLERITE AND GABBRO SILLS

Dolerite and gabbro sills are widespread within the Fortescue Group, the Weeli Wolli Formation and the Eel Creek Formation. Dolerite sills also intrude the Waltha Woora Formation and the Bangemall Group. Two of the sills are sufficiently large to be formally named the Davis Dolerite and the Cooya Pooya Dolerite.

The Davis Dolerite (de la Hunty, 1963) crops out in the southeastern part of the area. Generally about 30 m thick (de la Hunty, 1963, p. 27), the sill is exposed east of Mount Cooke where its outcrop area exceeds 50 km^2. Another large outcrop occurs south of the Davis River near Mount Divide.

The Cooya Pooya Dolerite (Kriewaldt and Ryan, 1967) is up to 100 m thick and consists of dolerite and very subordinate granophyre cropping out over 1 800km^2 in the district around Cooya Pooya homestead (Plate 1A). The dolerite intrudes the Hardey Sandstone, but is slightly transgressive as it locally occupies the boundary between this unit and the overlying Kylena Basalt. Its topographic expression is very distinctive, the dolerite cropping out in mesas and hills of strikingly black-weathered rock. Kriewaldt and Ryan (1967) suggested that the dolerite passes into lava near Mount Wohler and that the source of the intrusion is a feeder near Cooya Pooya homestead; large indurated blocks of sandstone and felsic to intermediate lava occur in the dolerite at Lockyer Gap, 6 km northwest of the homestead. Kreiwaldt and Ryan stated that the age of the intrusion is probably the same as that of the Gidley Granophyre, and also suggested that it might be similar to that of the Kylena Basalt.

GRANOPHYRE

Two large masses of granophyre are shown on Plate 1A. One, the Ragged Hills Granophyre has already been described and is situated on the eastern side of the Gregory Range. The second mass cropping out in the northwestern part of the Pilbara Block, around Dampier, has been named the Gidley Granophyre.

The Gidley Granophyre (de Laeter and Trendall, 1971) is an intrusion of granophyre and associated gabbro along the basal unconformity of the Fortescue Group. The main outcrop is in the Dampier Archipelago and the adjacent mainland and occupies an area of about 200 km². A differentiated coarse-grained gabbro forms the base of the intrusion. Gradations to feldspathic diorite and quartz diorite are common, and the assimilation of Archaean granitic rocks from the basement has resulted in some hybridization. Above the gabbro the main body of the intrusion is a fine- to medium-grained, porphyritic, blue-grey granophyre containing equal amounts of grey quartz, pink feldspar and dark ferro-magnesian minerals, and subordinate white feldspar. Basal arkosic sandstone of the Mount Roe Basalt has been metasomatized by the granophyre and small granophyric dykes intrude this formation on Enderby Island. The total thickness of the Gidley Granophyre is estimated to be 3 000 m. De Laeter and Trendall (1971) described the petrography of the intrusion before presenting isotopic evidence that its age is 2 196 ± 26 m.y. (recalculated to 2 150 ± 25 m.y.). Four samples define an isochron indicating an age of 2 620 ± 58 m.y. (recalculated to 2 567 ± 56 m.y.), but de Laeter and Trendall considered that this was probably fortuitous, chiefly because such an old date did not agree with pre-1971 geochronological results from the Fortescue Group. Such early results include 2 190 ± 100 m.y. age for felsic volcanics of the Jeerinah Formation and a 2 000 ± 100 m.y. age for the Woongarra Volcanics (Compston and Arriens, 1968). De Laeter and Trendall considered it improbable that the Mount Roe Basalt should be as old as 2 620 m.y. as this would involve a 500 m.y. time span for depositon of the Fortescue Group. Recent geochronology (e.g. a 2 600-2 650 m.y. age for the Hardey Sandstone, (Hickman and de Laeter, 1977) which conformably overlies the Mount Roe Basalt) however indicates that the older isochron may be more significant than previously supposed.

DACITE PORPHYRY SILLS

Proterozoic feldspar-phyric dacite porphyry sills intrude the Hardey Sandstone in the eastern part of the Pilbara Block (Plate 1A). The principal outcrops occur near Nullagine, Bamboo Creek and Boodalyerrie Creek, the total outcrop area is approximately 500 km² and the original extent of the sill complex or sill (the various outcrops could represent remnants of a once continuous sheet) is 8 000 km².

The porphyry near Bamboo Creek mining centre has been named the Bamboo Creek Porphyry (Noldart and Wyatt, 1962), and that near Nullagine is referred to as the Spinaway Porphyry (Lipple, 1975). Noldart and Wyatt mapped and described the southern and northern outcrops of porphyry as part of a single body and noted earlier divergence of opinion as to whether it was intrusive or extrusive. To the north of Nullagine the Spinaway Porphyry possesses a chilled upper contact against thermally altered shale, and between Bamboo Creek and Green Hole the Bamboo Creek Porphyry sends apophyses into the overlying Kylena Basalt and Tumbiana Formation. East of Bindoo Well, however, Dr. R. Thom (Hickman, 1975a) has noted pebbles of porphyry in overlying conglomerate of the Hardey Sandstone. If these clasts were derived from the Bamboo Creek porphyry the latter must be older than the upper part of the Hardey Sandstone. In the Meentheena area the body includes vesicular porphyritic dacite containing flow-banding and clasts of shale. This rock has the appearance of a lava, but it could be a high-level hypabyssal rock positioned close to the upper contact of the sill.

Trendall (1975b) has described the petrography of the porphyry in some detail; in brief, the rock consists of phenocrysts of albite to oligoclase, quartz and microcline set in a fine-grained grey or pink-grey quartzofeldspathic groundmass. Oligoclase phenocrysts generally range between 2 and 10 mm but locally measure up to 20 mm in length. Trendall dated the Spinaway Porphyry at 2 124 ± 195 m.y. (recalculated to 2 079 ± 191 m.y.) (R_{i_2} = 0.712 6) and the Bamboo Creek Porphyry at 2 820 ± 516 m.y. (recalculated to 2 761 ± 505 m.y.) (R_i □ 0.701 0). The latter result is expectedly old but the isochron is poor due to a small range in $^{87}Rb/^{86}Sr$ ratio of the ten samples used. The Spinaway Porphyry isochron is far better and probably gives a more reliable indication of the true age of the intrusion. It will be noted that the error limits of the two results just overlap at about 2 270 m.y.

ADAMELLITE STOCKS AND HORNBLENDE PORPHYRY DYKES

Stocks of hornblende adamellite ranging in size from 0.5 km across to 8 km long intrude Archaean rocks and the Fortescue Group between Bamboo Creek and Windywindina Creek. These intrusions and associated hornblende porphyry dykes, form a north-northwesterly trending belt 140 km long and 25 km wide. De la Hunty (1964) also recorded a dyke of "hornblende porphyrite" 3 km southwest of Sunday Hill, which extends the length of the intruded zone to 160 km.

The hornblende adamellite is a medium, even-grained granitic rock with randomly oriented hornblende laths partly altered to chlorite. The quartz content of the rock is locally so low that it grades into hornblende monzonite. The largest exposed stock is the Bridget Adamellite (Hickman, 1975a) situated 10 km southwest of Cooke Creek mining centre.

The hornblende porphyry dykes represent off-shoots from the adamellite stocks and generally trend north-northwest. They consist of phenocrysts of euhedral oligoclase and hornblende set in an aphanitic quartzo-feldspathic groundmass.

FELSIC DYKES

Many of the Proterozoic felsic dykes shown on Plate 1A occur in the above-mentioned zone of hornblende porphyry intrusion and are composed of that rock type. Elsewhere rhyolite and dacite dykes intrude the Koongaling Volcanics east of Ragged Hills, and the Mount Roe Basalt at Meentheena. East-northeast-trending dykes of felsic rock containing granophyric and granitic xenoliths crop out between Lalla Rookh homestead and Fred Well. Near Lalla Rookh homestead, Low (1965, p.9) described the rock as an 'acid trachytoid' variety. Farther west the rock is hybrid in nature and is probably a contaminated mafic intrusion of the Mundine Well Suite.

ARCHAEAN-PROTEROZOIC UNCONFORMITY

The western, southern and eastern limits of the Pilbara Block correspond to the surface of unconformity (Fig. 29) at the base of the Fortescue Group. The unconformity is currently used to define the boundary between Archaean and Lower Proterozoic rocks (Dunn and others, 1966). If the age of an unconformity is defined as the age of the bed resting immediately upon it, the age of the Archaean-Proterozoic unconformity in the Pilbara Block varies from one locality to another. This is because deposition of the Fortescue Group commenced in a number of separate basins (Hickman and Lipple, 1975; Hickman, 1975a, Fig. 5). Outside these early basins the

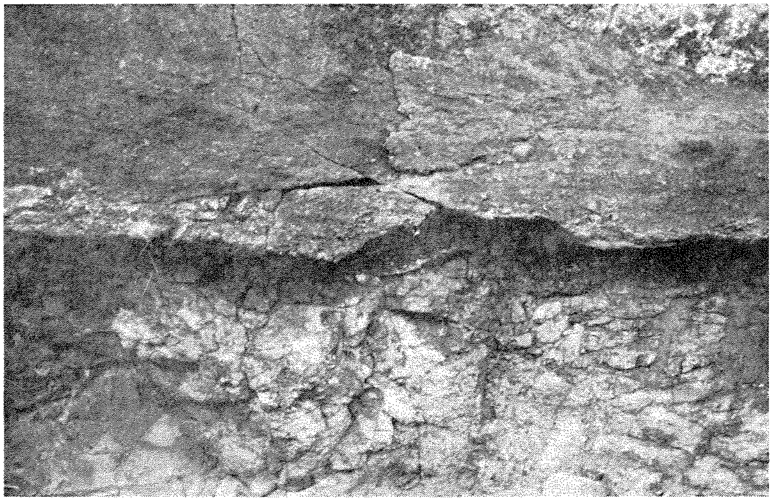

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Figure 29. The Proterozoic/Archaean unconformity 2 km east of 127 Mile Camp. Sandstone and conglomerate of the Hardey Sandstone overlie deeply weathered granodiorite

lowest formations of the group were never deposited. Over granitic terrain, for example, the basal formation is commonly the Kylena Basalt, or an even higher stratigraphic unit.

The Mount Roe Basalt and the Hardey Sandstone are generally restricted to areas where the underlying Archaean rocks belong to the Pilbara Supergroup rather than the granitic complex. Successively higher formations overlap underlying units in the lower part of the group until the Tumbiana Formation is reached. At this stage most of the early basins appear to have been filled and wedge-shaped formations give way upwards to tabular and sheet-like units. Differences in geometry between the lower and upper formations are conveniently illustrated by comparing the Hardey Sandstone with the Tumbiana Formation. To the west of Nullagine the Hardey Sandstone reaches a maximum thicknes of 1 000 m and wedges out laterally to 2 m thick within a distance of 20 km. By contrast, the Tumbiana Formation ranges in thickness from 50 m to 200 m but extends 540 km across the Pilbara Block from the Gregory Range to Cape Preston. The irregularity of the Archaean-Lower Proterozoic unconformity was first recognized by Maitland (1909, p. 118) and is further discussed by Kriewaldt (1964b) who noted the presence of abutment unconformities.

The late Archaean land surface consisted of granitic uplands, and depressions underlain by greenstones. Siliceous strata, such as quartzite, chert and BIF, were resistant to late Archaean weathering and formed strike ridges rising abruptly several hundred metres above the level of the surrounding countryside. Examples of such ridges are preserved at Warralong Creek, Shady Camp Well, Blue Bar, Lionel, Twenty Ounce Gulley, Coolbanacoula Pool and Nunyerry Gap. In general, relief seems to have been limited to between 500 and 1 000 m. Where Archaean granite underlies the unconformity this implies erosion of at least 15 km of rock (i.e. the minimum thickness of the Pilbara Supergroup), but much of this erosion probably took place during mid-Archaean times; conglomerates containing Archaean clasts occur in the Panorama Formation, the Gorge Creek Group and the Whim Creek Group.

The absolute age of the oldest Proterozoic formations in the area, the Mount Roe Basalt and the Koongaling Volcanics, is probably about 2 600 m.y. (the age of the Hardey Sandstone, according to Hickman and de Laeter, 1977) and certainly no less than 2 280 m.y. (Black Range dyke, Lewis and others, 1975). If the figure of 2 600 m.y. is accepted, the post-tectonic granitic plutons of the Pilbara Block must have been intruded only very shortly before the onset of Fortescue Group volcanism. Further geochronology (Rb-Sr, U-Pb and Sm-Nd) on the post-tectonic plutons and felsic lava in the Fortescue Group should reveal the maximum age of the unconformity with more accuracy.

CHAPTER 4

Phanerozoic

Phanerozoic rocks ranging in age from Permian to Quaternary crop out chiefly in the northern and eastern parts of the area (Plate 1A). Because this Bulletin is chiefly concerned with Archaean and, to a lesser extent, the Proterozoic geology of the area, the following descriptions of Phanerozoic strata are kept as brief as possible.

PERMIAN

The Paterson Formation (Traves and others, 1956) contains fluvioglacial and glacial deposits of pebble beds, sandstone and claystone which crop out in the Oakover valley and near Shay Gap. Noldart and Wyatt (1962) referred to the unit as the "Braeside Tillite" but stratigraphic correlation between the Oakover valley and the Paterson Range (type area of the Paterson Formation) is now sufficiently well established to render this name obsolete.

The pebble beds are well cemented at depth but at the surface weather to form mounds containing unconsolidated boulders of quartz, quartzite, granite, chert, chert breccia, sandstone, basalt and schist. Most of the clasts are well rounded and range in size up to boulders 3 m in diameter; matrix is a blue-grey sandy claystone. Evidence of ice transport is provided by faceted and striated boulders. At Carawine Pool, Pearana Rock Hole, and in the Rudall Sheet area (Chin and others, 1979) the formation is

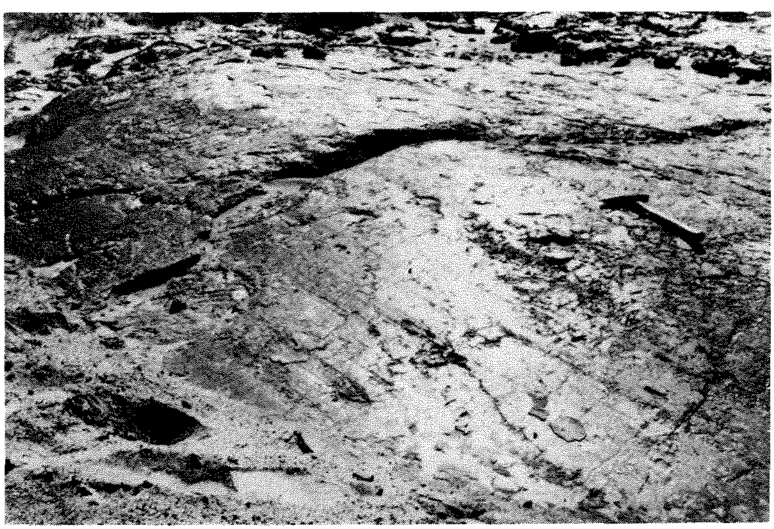

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Figure 30. Striated glaciated pavement 6 km northeast of Carawine Pool. The pavement is developed on the Proterozoic Pinjian Chert Breccia and overlain by Permian fluvio-glacial deposits of the Paterson Formation

underlain by glaciated pavements (Fig. 30). The configuration of grooving and striation on these surfaces indicates that ice movement was northwards.

The thickness of the formation ranges up to 250 m (e.g. in a drillhole 16 km east of Warrawagine) and may locally approach 500 m (on geophysical evidence). At the margins of the Oakover valley it lenses out against the Precambrian basement.

Spore and pollen grains in mudstone samples taken from drillholes 18 km northeast of Warrawagine homestead indicate an Early Permian (late Sakmarian) age and suggest a non-marine environment of deposition for the mudstone (Backhouse, 1976).

The pebble beds from a basal member of the formation and are overlain by cross-bedded fluvial sandstone and conglomerate. The sandstone is medium- to coarse-grained, poorly sorted and composed dominantly of quartz (although some beds contain a high proportion of feldspar) with a clay matrix. At Bunmardie Creek sandstone of this type was referred to as the 'Bunmardie Beds' by Noldart and Wyatt (1962), but this name is no longer applied.

MESOZOIC

The northeastern boundary of the Pilbara Block is defined by the basal unconformity of the Callawa Formation. The Callawa Formation (Traves and others, 1956) consists of moderately to poorly sorted conglomerate, sandstone and claystone. Good exposures are available around Shay Gap township, where cross-bedding is a conspicuous feature. Palaeocurrent directions have not been studied at Shay Gap but Traves and others (1956, p. 26) state that the trend is north or northeast at the head of Eel Creek. The formation is considered to be of fluviatile and deltaic origin deposited near the southern or southwestern margin of a large fresh-water Jurassic Lake (Traves and others, 1956, p. 28). At the type section, near the head of Eel Creek, the Callawa Formation is 52 m thick. The thickest measured section is 61 m. The only fossils recorded are plants including *Johnstonia, Cladophlebis, Pagiophyllum, Sphenopteris, Dictyophyllum, Brachyphyllum, Pachypteris, Ruffordia* and *Ginkgoites.* Brunnschweiler (in Traves and others, 1956) regarded the assemblage as Early Jurassic or Late Triassic in age, but White (in Veevers and Wells, 1961) re-examined the collection and believes that the forms are Late Jurassic or Early Cretaceous.

CAINOZOIC

SILICEOUS CAP ROCK

Fine-grained siliceous cap rock, commonly chalcedonic and in places passing laterally into the Oakover Formation (Tertiary calcrete) replaces carbonate rocks of the Carawine Dolomite between Warrawagine and Braeside. Areas of cap rock, too small to be shown on Plate 1A, occur over sandstone and ultramafic units. The age of the rock is considered to be Tertiary. In most areas it is deeply dissected by the present drainage system and appears to have formed at or near the level of the Hamersley Surface.

PISOLITIC LIMONITE

Flat-topped benches and mesas of Tertiary pisolitic limonite (including units correlated with the Poondano Formation (McWhae and others, 1958) and the Robe

Pisolite (de la Hunty, 1965a)) represent fossil drainage courses. The deposit is generally 5 to 10 m thick, cavernous, and contains abundant fragments of fossil wood replaced by limonite. Unsorted silty kaolinitic quartz sandstone is also a constituent. In most areas the pisolite occurs close to Archaean or Proterozoic BIF, but this is not always the situation (e.g. Poondano Rock Hole). The formation is a potential source of limonite-goethite iron ore (Chapter 7).

FERRUGINOUS DURICRUST

Tertiary laterite or ferruginous duricrust developed on the Hamersley Surface is widespread on high ground but generally forms outcrops only a few square kilometres in extent. The unit includes ferruginized sandstone, lateritized basalt and consolidated ferruginous breccia, and is most common above or adjacent to BIF. In general it contains too many impurities to be considered a potential source of iron.

GRAVEL

Dissected gravel deposits of Tertiary to Quaternary age represent ancient talus slopes, outwash fans and fluviatile deposits. The unit is composed of polymictic pebble beds in which rounded to angular clasts of rock are loosely bound by coarse sand. In some places the lower beds are carbonate-cemented and the unit commonly overlies kankar. On the plains it is considered to form part of the Yule Surface (Kriewaldt and Ryan, 1967). At Friendly Creek and Coondina the basal sections of this unit contain economically important concentrations of detrital cassiterite.

CALCRETE

Extensive deposits of partly or entirely silicified calcrete occur in the valleys of the Oakover and Fortescue Rivers, and isolated small mesas occur at Tabba Tabba, Cunmagunna Hill, Yarrie and 17 km southwest of Nimingarra. Low outcrops of calcrete occur 10 km southeast of Strelley homestead.

In the Oakover valley Noldart and Wyatt (1962, p. 70) named the unit the Oakover Formation and assigned it a Tertiary age (see also Maitland, 1904, p. 6, 31; Clapp, 1925, p. 60; Finucane, 1938e, p. 4). The Oakover Formation is generally between 5 and 30 m thick and consists of partly silicified calcrete containing and overlying beds of calcareous sandstone. The unit unconformably overlies the Paterson Formation and is locally overlain by laterite. In the Oakover valley it appears to be a lacustrine deposit associated with the Hamersley Surface. At Braeside oolitic carbonate rock has yielded marine fossils of Miocene or younger age. These fossils and the relationship between the oolite and the Oakover Formation merit further investigation because their presence seems to indicate a Tertiary marine incursion (200 m above present sea level) into the western part of the Canning Basin. Undiagnostic ostracods are recorded by Veevers and Wells (1961, p. 197).

In the Fortescue valley cavernous calcrete occurs close to the level of the valley floor and also along the southern margin of the Chichester Range. The topographically higher deposits are dissected by gullies up to 20 m deep. The calcrete is an important aquifer, a bore field at Millstream supplying the coastal towns of Dampier, Karratha, Wickham and Cape Lambert with a total of 9×10^6 m^3 water per annum (Barnett and others, 1977). Gastropods and freshwater molluscs collected from the top of the calcrete are Pleistocene to Holocene in age (Barnett, pers. comm.) but the main body of the unit is probably significantly older. The deposit post-dates dissection of the Hamersley Surface, overlies limonitic pisolite and probably pre-dates capture of the Fortescue River by the Gregory Gorge watercourse (Chapter 1). Its age is thought to be Late Tertiary or Early Pleistocene.

COLLUVIUM AND ALLUVIUM

Tertiary to Quaternary colluvium and alluvium forms dissected scree slopes and outwash fans adjacent to areas of high relief. The unit is related to the gravel deposits referred to above but is finer grained. In parts of the Oakover valley it is extensively ferruginized (e.g. at Skull Springs).

ELUVIUM OVER GRANITIC ROCKS

Quaternary eluvial sand containing quartz and feldspar grains with scattered fragments of granite, pegmatite minerals and vein quartz occupies much of the plain physiographic division. Lateral transport is locally evident on slopes, and the sand may be partly reworked by wind action.

SANDY AND SHELLY LIMESTONE

The Bossut Formation (Lindner, *in* Johnstone, 1961; Veevers and Wells, 1961, p. 199) is a unit of sandy calcarenite, which crops out discontinuously near the coast. It includes lithified dunes and beach and offshore bar deposits, and is equivalent to the Tamala Limestone (formerly Coastal Limestone) of the Perth and Carnarvon Basins. It is probably about 20 m thick near Port Hedland (Low, 1965) and attains a maximum proven thickness of 33 m in Samphire Marsh No. 1 Well (about 100 km to the north of the area covered by Plate 1A).

SUPRATIDAL AND INTERTIDAL CLAY AND SILT

Most sections of the coastline are fringed by a 1 to 15 km wide belt of supratidal and intertidal deposits. These include clay and silt in the mangrove swamps, saline grey mud and silt above the 'mangrove line' and calcareous clay, silt and sand on supratidal flats. Above the high-water line, sand and silt predominate over clay, and the deposits are partly fixed by grasses. Holocene silty sand containing shells of the bivalve *Anadara granosa* is also included in the unit.

ELUVIUM

Quaternary eluvium (other than that formed over granitic rocks) includes gilgai and pebbly sand. The gilgai unit occurs in poorly drained areas and generally overlies basaltic rocks or gravel deposits containing a large proportion of basaltic debris. It consists of clayey silt containing pebbles and boulders of the underlying strata. The clay absorbs water during periods of rainfall and consequently expands. Prolonged dry conditions cause it to lose water with the result that it contracts. This continual expansion and contraction produces a heaving effect in the surface layers with the generation of numerous small cracks and sinkholes; an irregular 'crabhole' surface results.

Dissected river gravels and the Paterson Formation are overlain by a thin veneer of pebbly alluvium in the Oakover valley and north of Warrawagine. The clasts are well rounded and include rocks not derived locally (i.e. they were transported a considerable distance prior to deposition in the underlying unit).

EOLIAN SAND

Wind-blown sand occurs chiefly in the northeast part of the area where it forms the surface of the Great Sandy Desert. Lateral transport from the east-southeast is obvious from the orientation of numerous seif dunes. Coastal dune sand consists of shelly material blown inshore from the Indian Ocean and piled up in ridges up to 20 m high.

COLLUVIUM

Quaternary scree and outwash fans containing lithic sand, gravel and boulders flank most of the hills and escarpments. Clasts are typically angular or subangular, depending on distance of transport. Most of these deposits are still in the process of formation.

ALLUVIUM

Recent alluvium, consisting of sand, silt and gravel occupies the present drainage channels. Finer alluvium is preserved on the wide flood plains of the various rivers and older Quaternary alluvium covers large sections of country around the lower reaches of the main rivers. This relatively old alluvium consists of reworked reddish brown sand, silt and sandy clay with belts of pebbly sand along old drainage courses. Many of the old drainage courses are visible from the air and some are flanked by levees.

CHAPTER 5

Geochemistry

INTRODUCTION

It is surprising that an area, which contains some of the world's best exposed greenstone belts attracted no systematic geochemical investigation until recently (Hallberg, 1974). One reason for this apparent lack of interest, apart from the isolation of the area, may have been the belief that extensive alteration of the volcanics lowered the probability of obtaining meaningful results. Hallberg's (1974) report appeared to confirm this; from 369 samples of volcanic and intrusive rocks collected, only 28 were considered suitable for analysis, the remainder containing unacceptable amounts of carbonate. However, more encouraging results were obtained from the granitic rocks (Blockley, 1973 and 1980; Oversby, 1976), where alteration is chiefly confined to surface weathering.

The Survey's recent remapping of the eastern part of the Pilbara Block indicated that, although alteration was widespread in the Pilbara Supergroup, relatively fresh rocks did exist in many areas. Over 30 felsic volcanic rocks were analysed (Hickman and Lipple, 1975, p. 74-79) and found to contain little carbonate (average CO_2 content 1.02 per cent). Having established the stratigraphy of the Pilbara Supergroup (Hickman and Lipple, 1975), the Survey considered the feasibility of a regional geochemical study. In 1975, a joint project was organized with the Bureau of Mineral Resources, Canberra, and by the end of 1977 almost 500 volcanic rocks had been analysed for all major elements and about 20 trace elements. The main aims of the project were to:

(1) determine the geochemical characteristics of the various volcanic units;

(2) identify anomalies which might have economic significance, and assess possible stratigraphic controls of mineralization;

(3) determine original geochemical affinities of the rocks, and attempt to obtain their primary igneous chemical classification;

(4) determine any stratigraphic chemical variations and assess the use of these in stratigraphic correlation;

(5) interpret the petrogenetic and tectonic significance of any such variations;

(6) discriminate between primary igneous chemical trends and secondary alteration effects and investigate possible correlations between degrees of alteration and trace metal redistribution; and

(7) collect suitable material for specialized studies, such as REE and isotopic analysis, part of which might be carried out in collaborative studies with other organizations (within the framework of the International Geological Correlation Program project "Archaean Igneous Geochemistry").

The results of this project will be published in a series of papers jointly written by officers of the Geological Survey and the Bureau of Mineral Resources, and consequently no detailed discussion is attempted in this bulletin. However, the data are used to make some preliminary observations.

GRANITIC ROCKS

The geochemistry of granitic rocks in the Mount Edgar, Shaw and Yule Batholiths is described by Blockley (1980) using analyses of 123 samples. This section of the bulletin summarizes Blockley's data and presents analyses of 52 additional rocks (Appendices A-C). These samples were collected from the Carlindi, Corunna Downs, Mount Edgar, Muccan, Shaw and Yule Batholiths, and from the North Pole Adamellite, Yilgalong Granite, Peawah Granodiorite and the John Bull Syncline (Pilbara Well area). Generalized petrographic descriptions of these granitic masses are given in Chapter 2.

Blockley (1980) states that the post-tectonic intrusions are chemically distinguishable from the older complex of pre- and syntectonic granitic masses. The post-tectonic intrusions have higher SiO_2, Be, Rb, Nb, Sn and U contents and K/Na, K/Rb and Rb/Sr ratios, but lower TiO_2, total iron, MgO, CaO and Sr contents and Th/U ratios than the older rocks. Other elements such as Li, F, Cu, Zn and Zr vary erratically. The post-tectonic intrusions are predominantly composed of adamellite whereas the older granitic complex is foliated, migmatitic and gneissic, and chiefly composed of granodiorite. Although adamellite of the older complex has a major element chemistry similar to that of the post-tectonic suite, K/Rb, Ca/Sr, Rb, Sr, Nb and Th/U can still be used as distinguishing criteria. Thus, the chemical differences between the two rock types are not merely those associated with varying degrees of fractionation.

One of Blockley's main aims was to explore the possibility of recognizing "tin granites" on the basis of whole-rock and biotite-chlorite chemistry. Not all the post-tectonic intrusions possess associated tin mineralization, but those which do (e.g. the Moolyella Adamellite, Cooglegong Adamellite, Spear Hill Adamellite and Numbana Granite) have anomalously high tin contents (generally 5-20 ppm). Much of the tin is contained in biotite (Blockley, 1980).

The new analyses presented in this bulletin were made on samples selected to compare other batholiths and plutons of the east Pilbara with those studied by Blockley. This has provided more information on the range of compositions within the older complex, and has confirmed field evidence of newly discovered post-tectonic intrusions at Talga River, Red Rock Creek and Sampson Creek.

Figures 31 and 32 examine the Rb/Sr ratios of the various batholiths and plutons. The established "tin granites" possess Rb/Sr ratios higher than 5.0 whereas rocks of the older complex generally have ratios of less than 1.0. Figure 32 uses Blockley's findings to draw dividing lines between the fields of the post-tectonic, tin-bearing granitic plutons and the foliated older granitic rocks. Ten plutons, which, on field evidence, were suspected of being post-tectonic and possible hosts to tin mineralization all plot within or close to the "tin granite" field. Appendix C shows that the average tin content of these plutons is 4.7 ppm whereas the average tin content of the older complex (Appendix A) is only 2.7 ppm. Figures 33 and 34 illustrate the variations in K and Rb within granitic rocks of the Pilbara Block. Figure 33 summarizes Figure 22 of

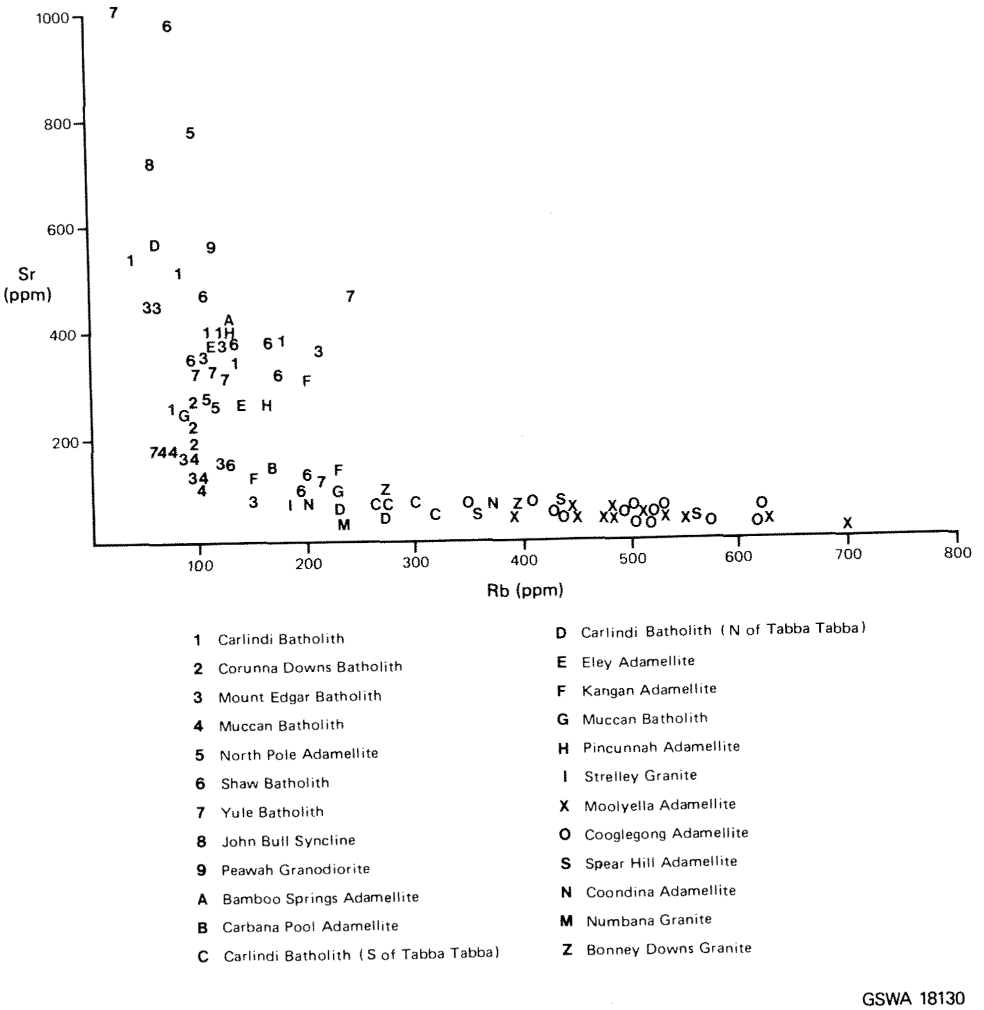


Figure 31. Distribution of Rb and Sr in the granitic rocks.

Blockley (1980) and adds a field boundary (> 300 ppm Rb, > 3 per cent K) which excludes all Blockley's samples from the older complex. Figure 34 plots analyses listed in Appendices A-C. Eight of the ten plutons lie within or very close to the post-tectonic field but the Mondana Adamellite and the Talga River intrusion are slightly more distant.

Figures 35 and 36 examine CaO/TiO_2 ratios. CaO and TiO_2 co-vary, presumably because Ti is present in the form of sphene. Several interesting points arise from these figures. Firstly, the post-tectonic granitic rocks contain less CaO and TiO_2 (generally 1.5 per cent CaO and less than 0.3 per cent TiO_2) than the older complex. Secondly, individual batholiths and plutons have different CaO/TiO_2 ratios; the Shaw Batholith, for example, appears to have a low CaO/TiO_2 ratio, whereas the Mount Edgar and Muccan Batholiths have a high ratio. Differences in CaO/TiO_2 ratios are more striking on Figure 36 which compares the Cooglegong Adamellite with the Moolyella Adamellite (these plutons are the two main sources of tin). Except for two samples

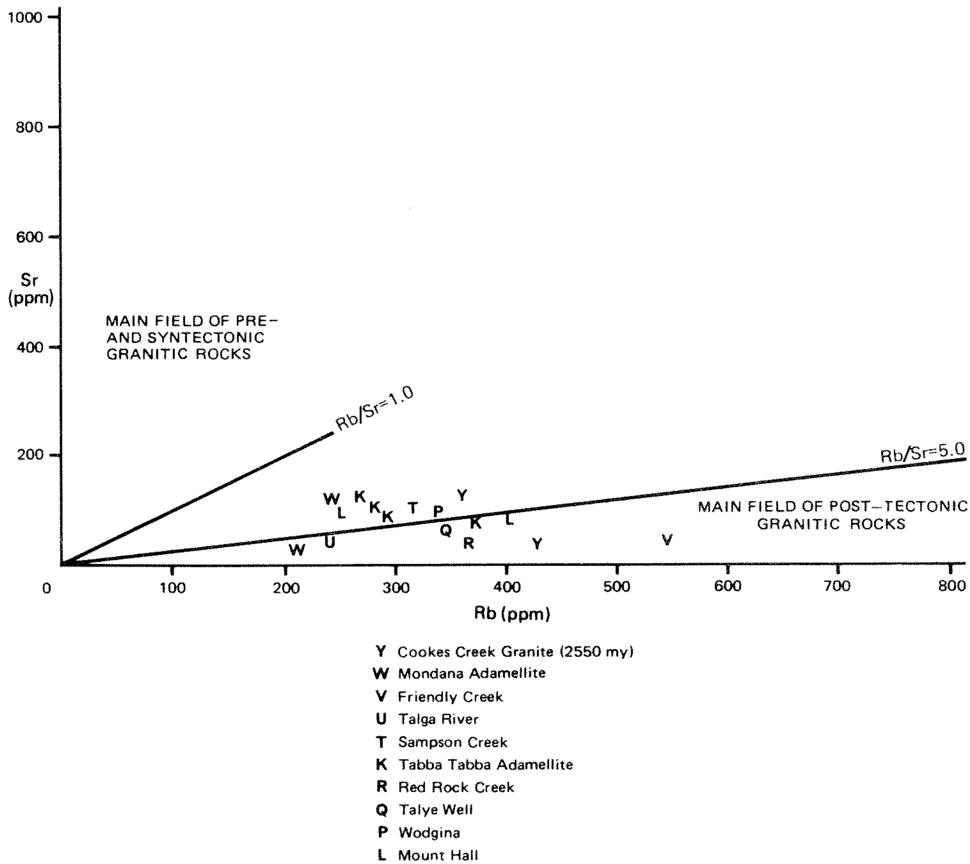


Figure 32. Distribution of Rb and Sr in known and postulated post-tectonic intrusions.

from the Cooglegong Adamellite, which have undergone a certain amount of contact alteration (one is partially melted), the data indicate two different trends.

Figure 37 shows that trace element geochemistry (in this case Nb and Th) can be used not only to separate rocks of the older complex from post-tectonic rocks but that it also indicates chemical differences between the batholiths. Relatively few samples have been analysed for these particular elements, but the differences appear to be quite marked.

The relative proportions of K_2O, Na_2O and CaO (calculated on the basis of weight) are examined in Figure 38. Blockley (1980) found that the post-tectonic granitic rocks were clustered within a relatively small field around 45 per cent K_2O and 10 per cent CaO. Most of the rocks from the older complex are far more sodic and calcic. The same result is obtained from the analyses in Appendices A-C (most of which are new analyses unavailable to Blockley). The sample from Talye Well is slightly more sodic than the post-tectonic granites. This particular rock comes from an area originally mapped as belonging to the older complex (Hickman, 1977a). It is from a foliated biotite adamellite that contains numerous blocks of well-foliated granodiorite.

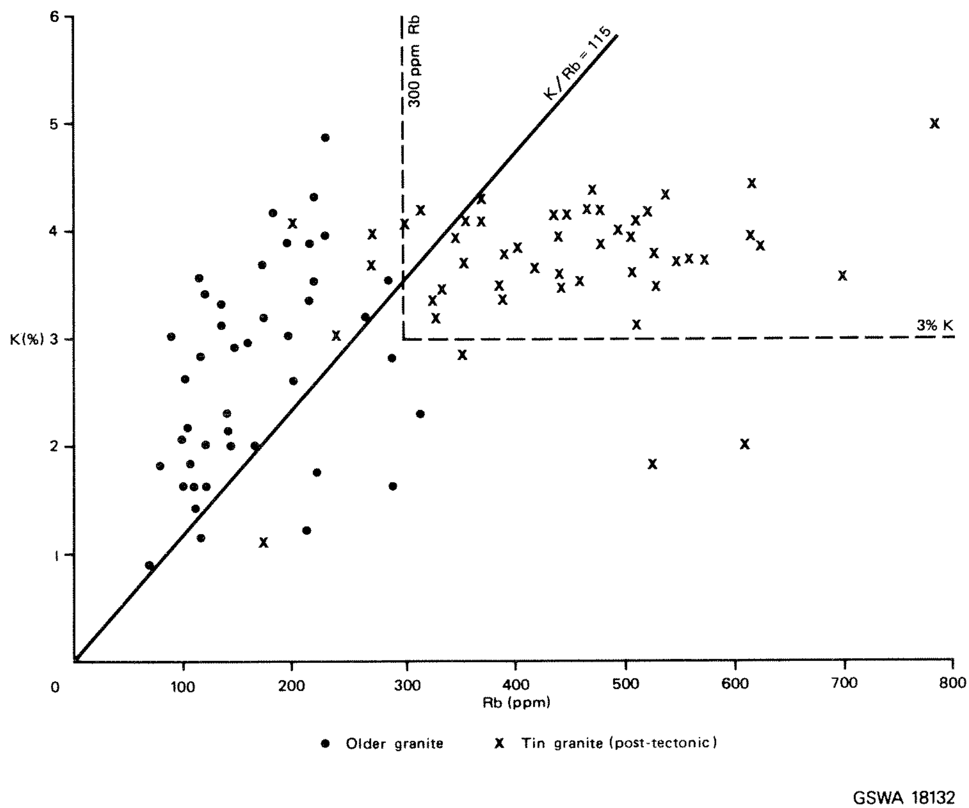


Figure 33. Distribution of K and Rb in granitic rocks. Analysed by Blockley (1980)

The age of this rock remains uncertain.

Because field evidence indicates the porphyritic intrusions are generally younger than other constituents of the older complex, their chemistry is tabulated separately (Appendix B). Figure 38 shows that, on the basis of $K_2O/Na_2O/CaO$, the mean composition of the porphyritic rocks is intermediate between that of the older complex and the post-tectonic intrusions. Figures 31 and 34 confirm this generalization.

In most respects, the Bamboo Springs Adamellite, the Carbana Pool Adamellite, and the Pincunah Adamellite are chemically similar to the older complex, but porphyritic rocks of the Carlindi Batholith are chemically more closely affiliated with the post-tectonic intrusions. The three former plutons contains well-foliated rocks, and, apart from being porphyritic, outwardly resemble rocks of the older complex. The Bamboo Springs Adamellite and the Carbana Pool Adamellite are intruded by post-tectonic plutons, but both intrude foliated gneissic and migmatitic granodiorite and tonalite.

Porphyritic adamellite at the 40 mile Quarry (Mount Newman Railway) crops out almost continuously for 25 km to the northeast and east. The rock is massive and weakly foliated. Oversby (1976) recognized a metamorphic age of 2 245-2 207 m.y.; but was unable to determine the rock's primary age. Chemical evidence (note 'C' symbols in Figs. 31, 34, 35 and 38) suggests a close relationship to the post-tectonic intrusions.

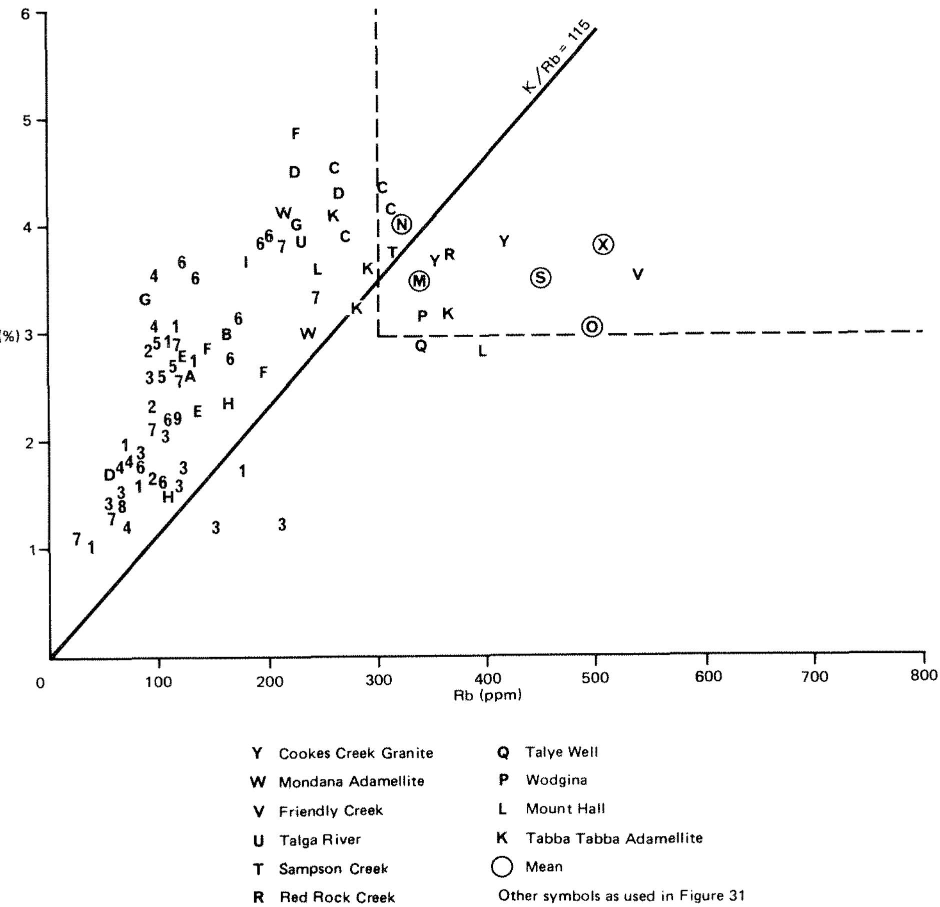


Figure 34. Distribution of K and Rb in rock analyses presented in Appendices A-C.

ORIGIN OF THE GRANITIC ROCKS

The average Na_2O content of the pre- and syntectonic rocks (i.e. the older complex) is 4.4 per cent; CaO and K_2O are 2.2 per cent and 2.8 per cent respectively. Le Maitre (1976) reported the world average composition of granodiorite to be 3.83 per cent CaO, 3.75 per cent Na_2O and 2.73 per cent K_2O (885 analyses) so that the Pilbara rocks are abnormally sodic (see also Fig. 39).

Glikson and Sheraton (1972) stated that an origin of early (> 3 000 m.y. in the Pilbara Block) sodic magmas through anatexis of sediments can be ruled out because Archaean sediments possess high K values relative to trondhjemite, tonalite and granodiorite. Tarney (1976) used TiO_2 and SiO_2 abundance levels to argue that the bulk of Archaean gneisses cannot be derived from sediments. Figure 40 shows that the TiO_2 and SiO_2 distribution patterns of the Pilbara granitic rocks are also inconsistent with derivation from sediments. In passing, it is interesting to note that although TiO_2 and SiO_2 exhibit a negative correlation in each of the Pilbara's three main granitic groups, TiO_2 increases relative to SiO_2 from the older complex, through the porhyritic

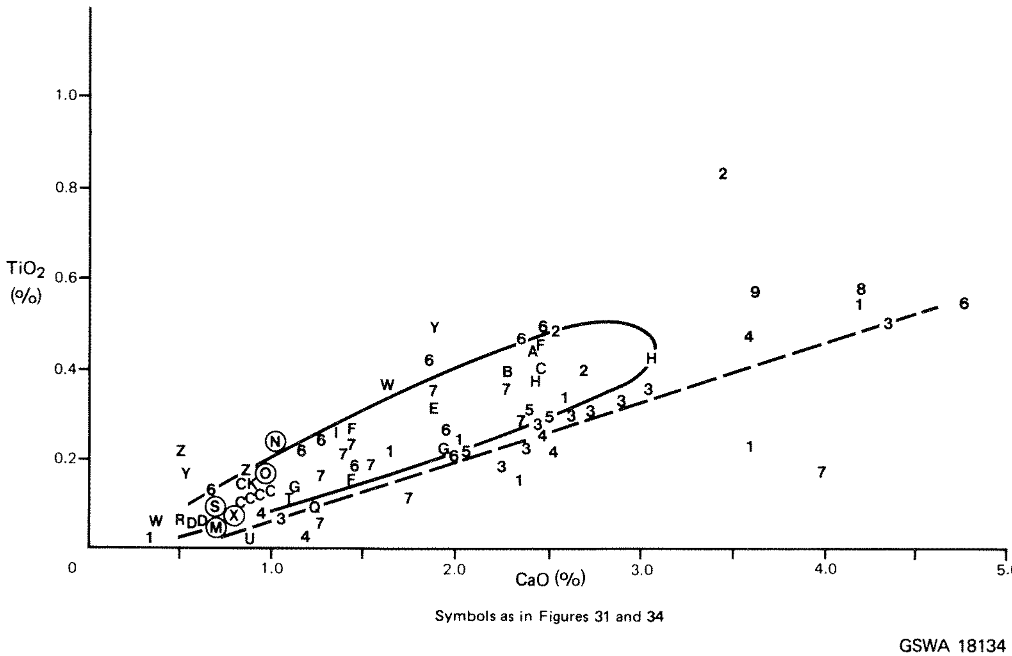


Figure 35. Distribution of TiO_2 and CaO in the granitic rocks.

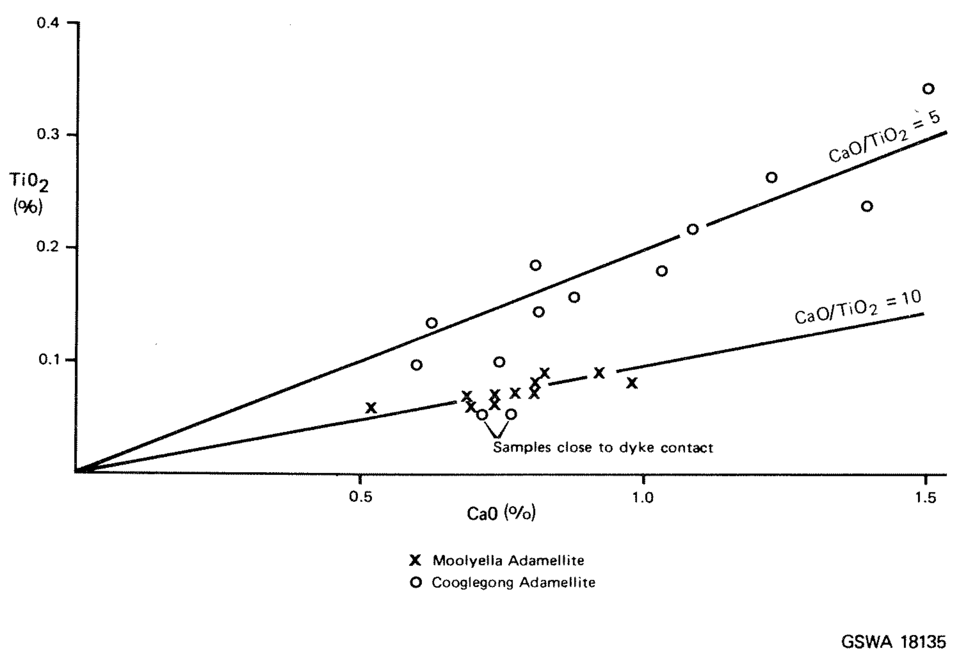


Figure 36. Distribution of TiO_2 and CaO in two post-tectonic intrusions.

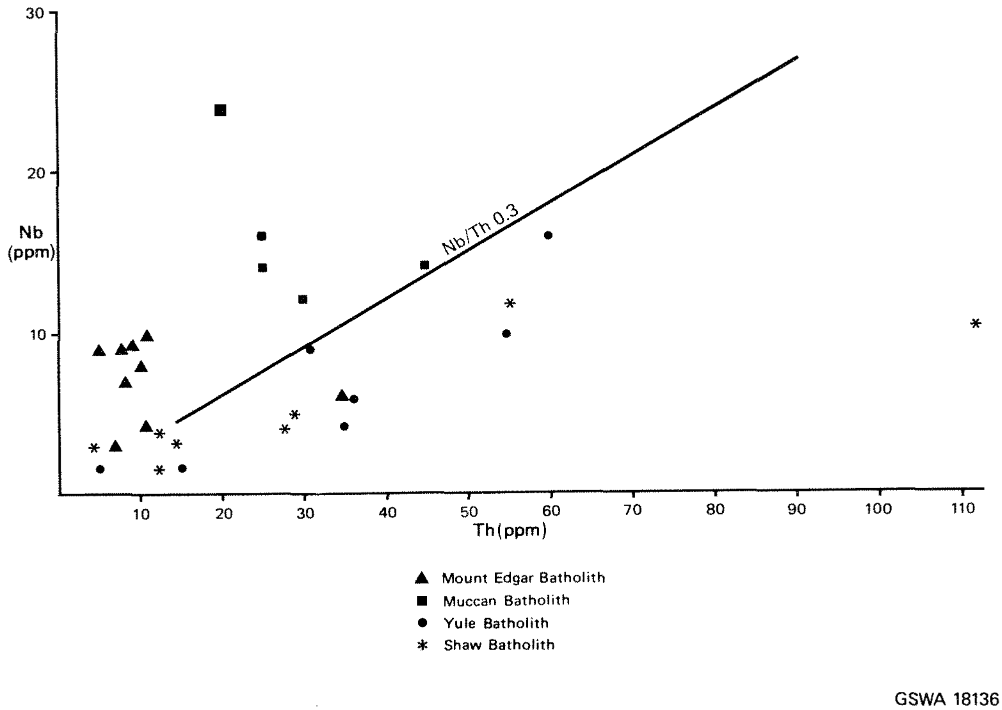
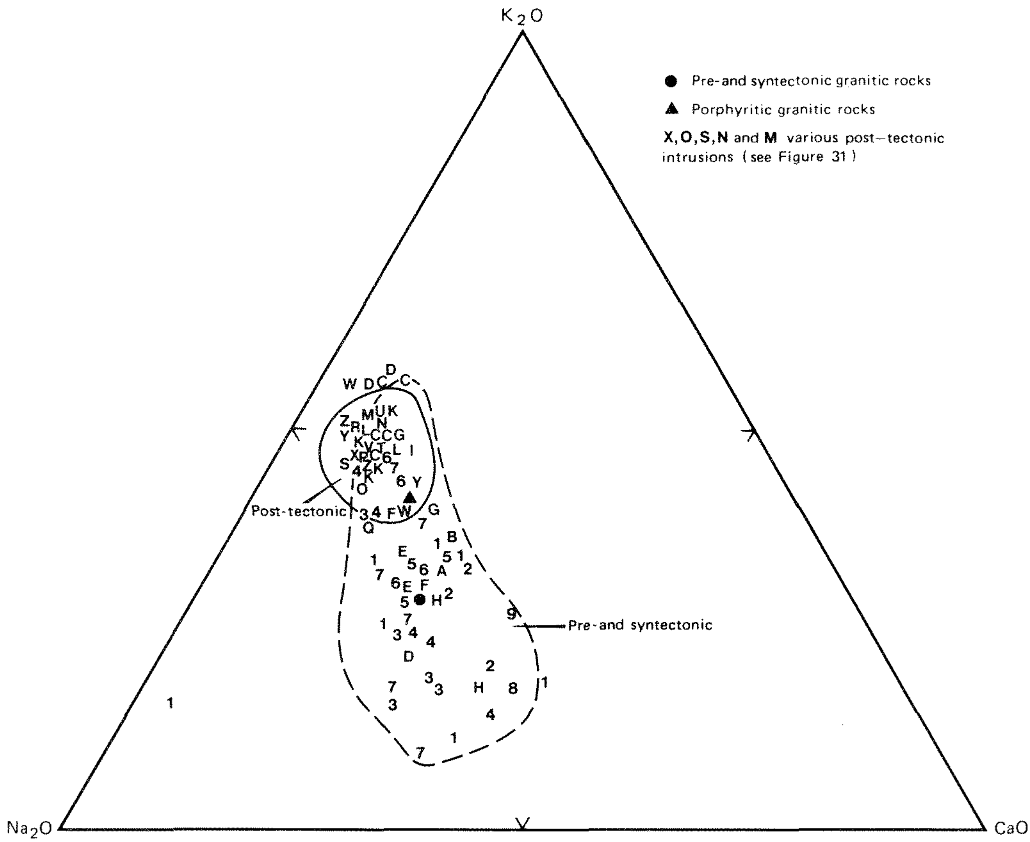


Figure 37. Distribution of Nb and Th in four of the batholiths.

intrusions to the post-tectonic intrusions. High Ba/Rb and K/Rb ratios and low K/Ba, K/Sr and Rb/Sr ratios indicate that much of the older complex was derived from relatively unfractionated liquids. Because only small volumes of granitic magma can be generated by direct partial melting of peridotite, Glikson (1971) favoured a two stage process involving partial melting of peridotite to form basic igneous rocks, followed by partial melting of these to yield sodic granitic rocks (Green and Ringwood, 1968). Similar models were proposed by Ringwood (1974) and Arth and Hanson (1975). Thus, part of the older complex may have been derived by partial melting of the Warrawoona Group, probably at deep crustal levels beneath the greenstone synclines.

Various workers (e.g. Glikson, 1976b) have argued that granitic rocks with low concentrations of the large-ion lithophile (LIL) elements (with the exception of Sr and Ba which tend to be concentrated in early potassic minerals) are unlikely to have been derived by reworking earlier sialic crust because initial partial melting would produce rocks rich in LIL elements and these are generally absent in the older granitic rocks (> 3 000 m.y.) of shield areas. Inspection of Appendix A and Figures 31, 33, 34 and 37, however, reveals that fractionated rocks of this type are not uncommon in the older complex of the Pilbara Block. About 8 per cent have Rb/Sr ratios greater than 1.0 and in 15 per cent of the analyses the K/Rb ratio is less than 150. Two of the rocks (GSWA 15233 and 15275), used by de Laeter and others (1975) to generate a ten-point isochron indicating an age of 2 951 ± 83 m.y. (recently recalculated to 2 889 ± 81 m.y.) (R_i = 0.7020 ± 0.0010) for part of the Shaw Batholith, have Rb/Sr ratios of 1.12 and 4.38. Both of these rocks, though assigned to the older complex, intrude foliated gneissic and migmatitic rocks.

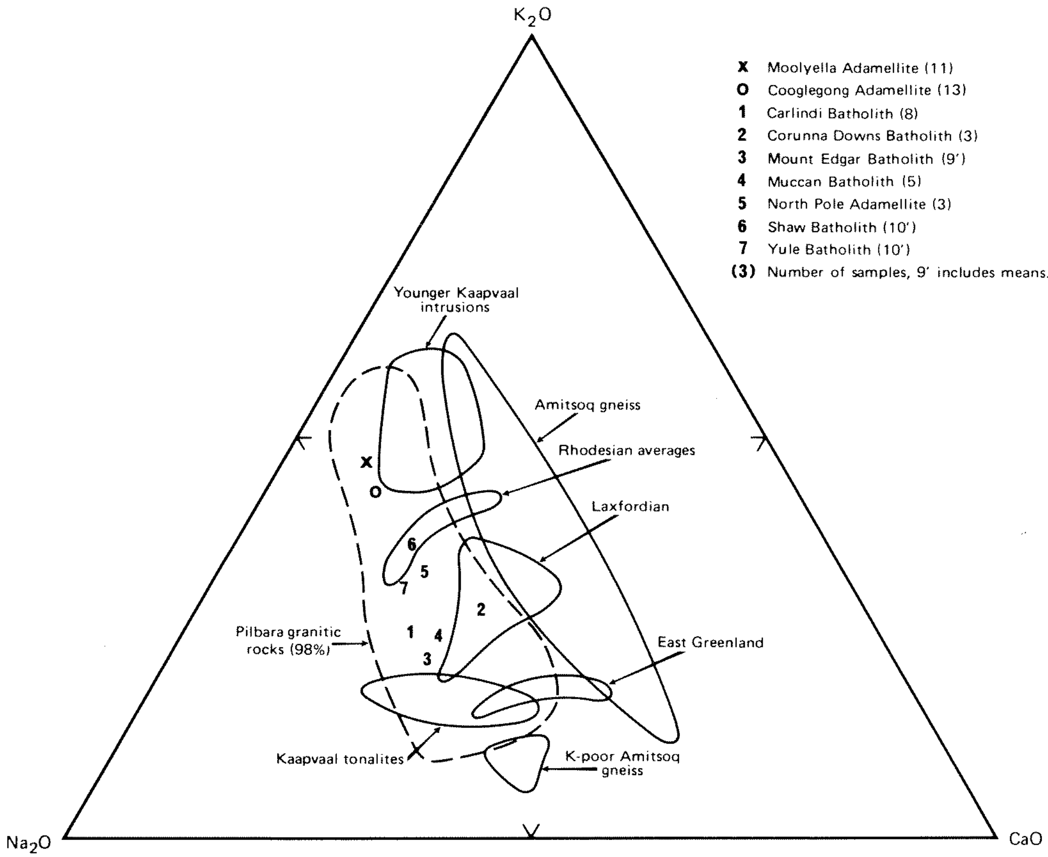


GSWA 18137

Figure 38. $K_2O/Na_2O/CaO$ by weight for the granitic rocks.

As yet, insufficient geochronological work has been undertaken in the Pilbara Block to determine the range of ages and initial $^{87}Sr/^{86}Sr$ ratios in the older complex. Thus, low initial ratios obtained on the few granitic masses studied so far cannot be taken as proof that the isotopic ages obtained (generally about 3 000 m.y.) closely approximate the age of all the granitic rocks in the batholiths. Also, there remains the possibility that locally extensive remelting of early sialic rocks may have been accompanied by losses in radiogenic strontium giving a false impression that the resulting granitic magmas were derived from the mantle. Such a process was advocated by O'Hara (1977, p. 196) who envisaged equilibration of Sr isotopes to upper mantle ratios in the Scourie gneiss complex of Scotland.

The origin of the post-tectonic rocks was discussed by de Laeter and Blockley (1972), de Laeter and others (1975) and Blockley (1980). In contrast to the older suite of granitic rocks, the post-tectonic plutons are fractionated and contain high K_2O, Be, Li, Nb, Pb, Rb, Sn, Th and U, and high Rb/Sr, K/Ba and K/Sr ratios. Initial $^{87}Sr/^{86}Sr$ ratios are approximately 0.74 to 0.73; this is consistent with derivation by partial melting (as opposed to near complete fusion) of pre-existing crust, or with a product of fractional crystallization (McCarthy and Cawthorn, 1980; McCarthy and Groves, in press). Blockley (1980) comments that fractionation is most advanced



GSWA 18138

Figure 39. $K_2O/Na_2O/CaO$ by weight, comparing granitic rocks of the Pilbara Block (175 samples) to those of other Archaean complexes (Lambert and others, 1976).

close to the roofs of the plutons, which probably testifies to late-stage magmatic differentiation.

The average chemical composition of the porphyritic granitic plutons is intermediate between that of the bulk of the older complex and the post-tectonic rocks. Some of the porphyritic units are probably true post-tectonic intrusions whereas others pre-date the main episode of deformation and are chemically similar to the older complex.

FELSIC VOLCANIC ROCKS

The following discussion of rhyolite and dacite chemistry is based on 129 whole-rock analyses from the Warrawoona Group. Appendix D lists analyses previously presented by Hickman and Lipple (1975) and Appendix E summarizes data obtained jointly with the Bureau of Mineral Resources, Canberra. It is immediately obvious from Appendix E that the Duffer Formation and the Wyman Formation are chemically different: the Duffer Formation is predominantly dacitic whereas the Wyman Formation is entirely composed of rhyolite. Trace element concentrations

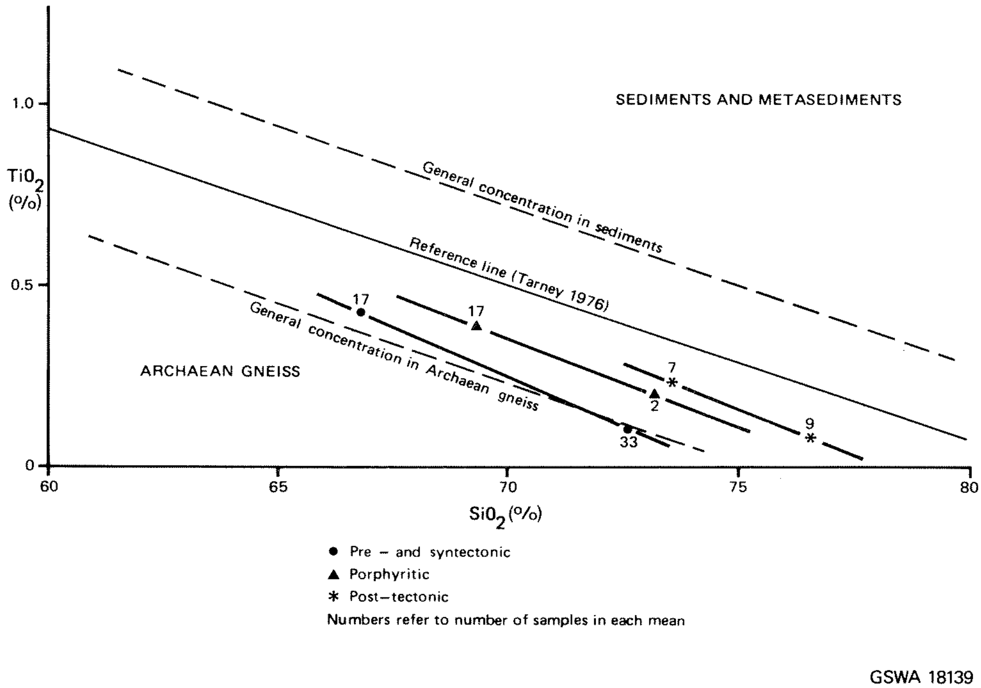


Figure 40. TiO_2/SiO_2 distribution, comparing granitic rocks of the Pilbara Block to Archaean gneiss and sedimentary rocks (based on Tarney, 1976)

reflect this difference. Column 4 reveals that the upper part (top 500 m of a 4 000 m succession) of the Duffer Formation at Bowls Gorge, 14 km north of Marble Bar is markedly more fractionated than the underlying part of the formation (this point is amplified later), but otherwise the Duffer Formation is relatively homogeneous. This contrasts with the Wyman Formation which at the three main localities sampled (see also Appendix D, nos. 1 and 2) is chemically quite variable. The four samples collected at Emu Creek (Appendix E, no. 9) are unusual in many respects, especially TiO_2, Fe, MgO, Na_2O, K_2O, P_2O_5, Cr, Cu, Th and V. If alteration is responsible, its effects were remarkably uniform because standard deviations are low despite the fact that the samples were collected over a distance of 500 m across strike. Most features (chemical and petrographic) of the rock indicate that it is rhyolite, but the relatively high TiO_2, Cr and V values are puzzling.

If the four problematical samples from Emu Creek are temporarily ignored, the chemical differences between the Wyman and Duffer Formations become more pronounced. A selection of rhyolites from the Duffer Formation (Appendix E, no. 5) reveals that these differences are not merely those which can be attributed to differing mineralogy. Duffer Formation magma appears to have been genuinely richer in total iron, MgO, CaO, Ba, Cr, Cu, Li, Ni, Sr, V and Zn but poorer in Pb and Th; also, it possessed higher K/Rb and far lower Rb/Sr ratios. These differences are closely parallel to those between the foliated granitic complex and the post-tectonic granitic intrusions. It is highly probable that part of the foliated complex is consanguinous with the Duffer Formation, a conclusion also reached by Hallberg and Glikson (in press). Hickman (1975a) suggested that certain of the post-tectonic intrusions (e.g. at Wallabirdee Ridge) may be related to the Wyman Formation. This raises the question of the age of the Wyman Formation.

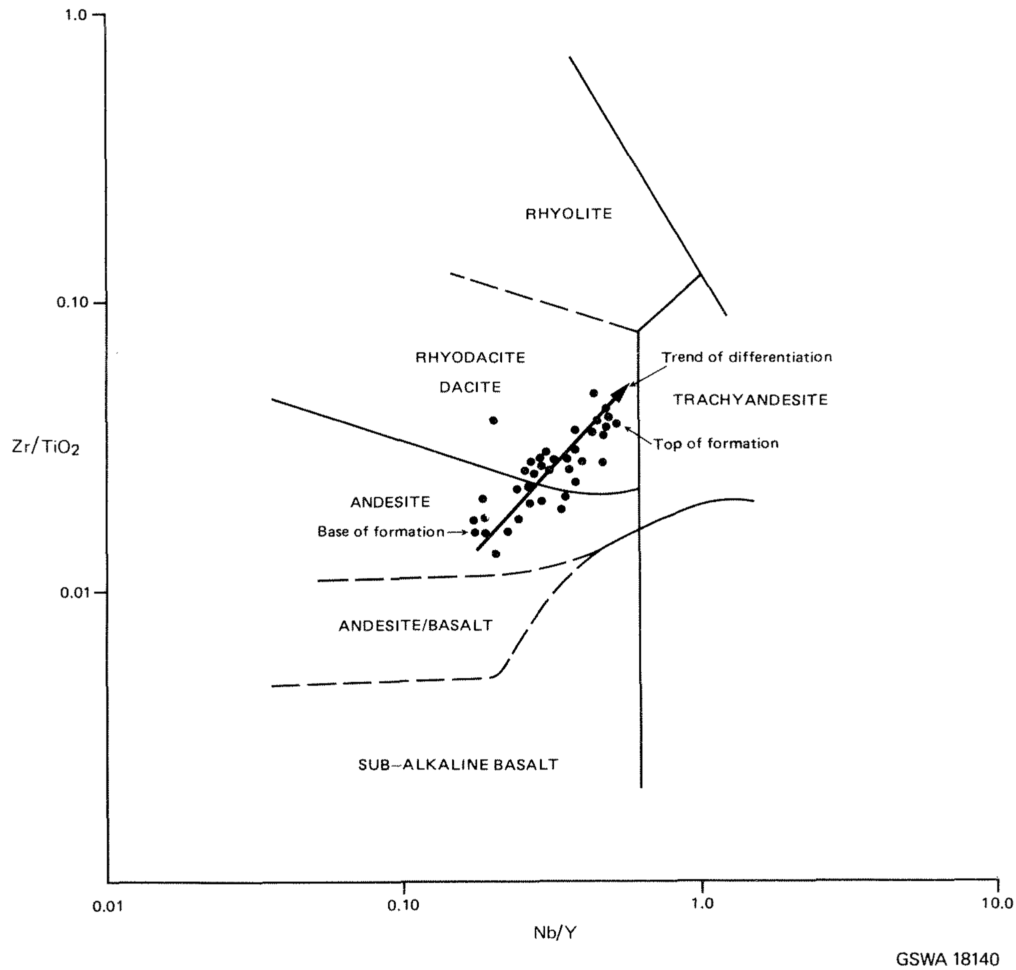


Figure 41. Zr/TiO_2:Nb/Y diagram (after Winchester and Floyd, 1977) for the Duffer Formation between Bowls Gorge and the Coongan River

Only one systematic sampling traverse has so far been made across the entire stratigraphic thickness of a felsic formation. This traverse is located east of Bowls Gorge, 14 km north of Marble Bar. Here the Duffer Formation which is locally about 4 000 m thick, was sampled at vertical intervals of 50 to 200 m. The resulting chemical data reveal a clearly defined trend of increasing magmatic differentiation from base to top. Figure 41 (based on criteria established by Winchester and Floyd, 1977) uses elements least affected by metasomatic redistribution to show that the formation grades upwards from andesite to dacite and rhyodacite. Figure 42 plots changes in the concentration levels of Th, La, Ce, Fe, V and Ni according to stratigraphic position. All these elements vary consistently with respect to the Zr/TiO_2 ratio (an index of magmatic differentiation). Th, La and Ce exhibit a strong positive correlation with Zr/TiO_2 whereas Fe, V and Ni vary negatively to it. The positive correlation between Fe and V is striking, although taken in isolation these elements do not define a clear differentiation trend. The distribution of elements such as Mg, Ca, Na, K, Ba, Rb, Sr, and Cr is more erratic, indicating relative mobility during alteration (the effects of

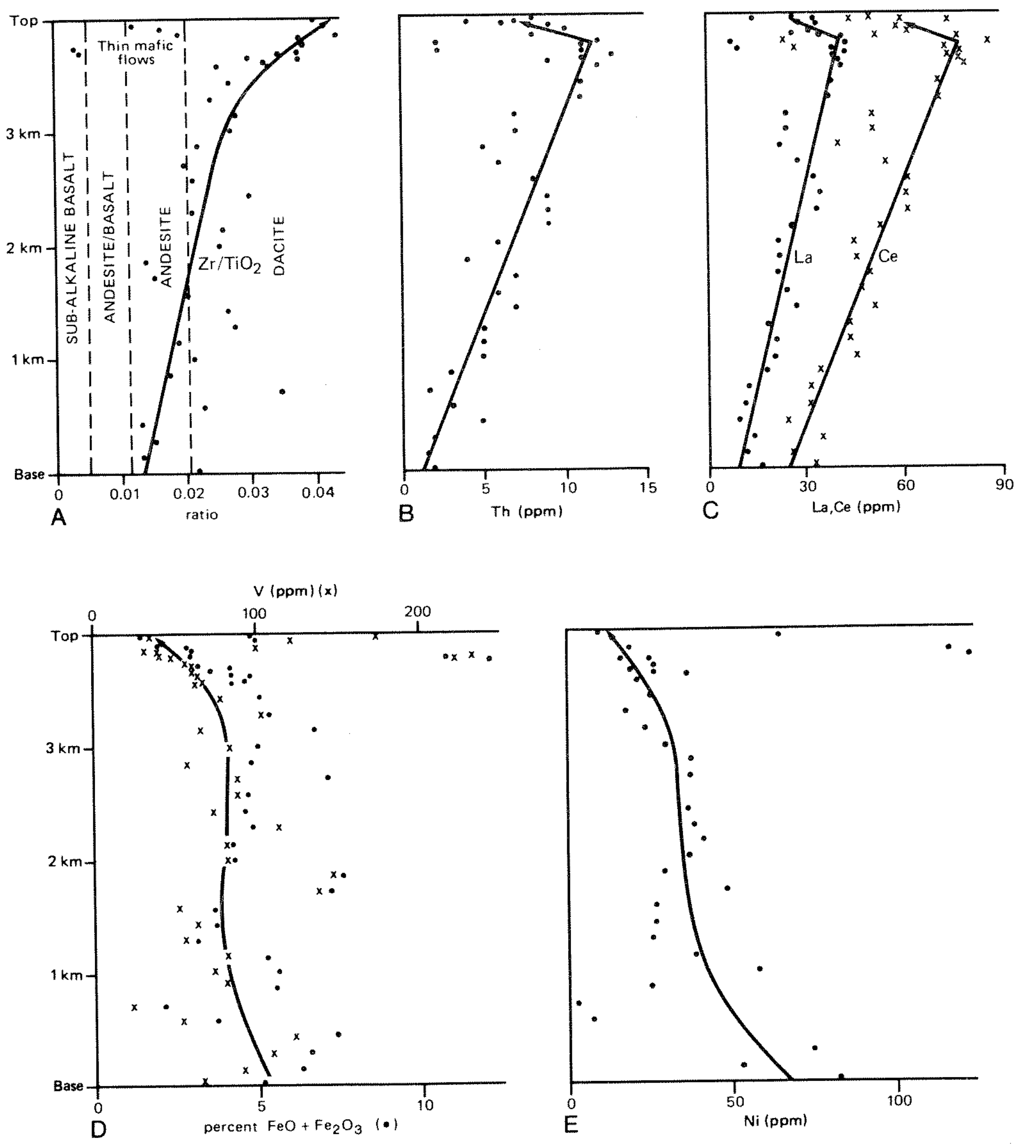


Figure 42. Differentiation trends in the Duffer Formation.

which are present to varying degrees in all the rocks). The K/Rb ratio shows a general tendency to decrease upwards from about 530 to 250 whereas Rb/Sr increases from 0.02 to 3.2, the stratigraphically highest sample possessing an exceptional ratio of 17. The Nb/Y ratio, an established indicator of alkalinity (Pearce and Cann, 1973; Winchester and Floyd, 1977), increases upwards from 0.15 to 0.55.

The mutually consistent and logical variation of the immobile elements in the Duffer Formation at Marble Bar is an extremely encouraging early discovery arising from the Survey's joint project with the Bureau of Mineral Resources. More detailed analyses of this and other stratigraphic sections are continuing.

Chemical analyses from silicified pillow lava at Soanesville reveal a similarity to the Duffer Formation except with respect to Ce, Cu, Ni and V. The pillow lava, once regarded as originally dacitic in composition (Lipple, 1973; Hickman and Lipple, 1975), may in fact be extensively altered basalt (Ce, Ni and V are relatively stable under alteration). The only pronounced chemical variation across pillow structures is a ten-fold zinc enrichment in skins relative to cores.

ORIGIN OF THE FELSIC ROCKS

The Wyman Formation contains no andesite or dacite, and conformably or unconformably overlies basalt of the Salgash Subgroup. Its highly fractionated chemistry is satisfactorily explained by partial melting of sialic crust. By contrast, the Duffer Formation is a calk-alkaline assemblage with generally high K/Rb and Na/K ratios. Recent andesite-dacite piles occur in island arcs and on continental margins, and such assemblages have also been erupted in intracontinental orogenic chains. Jakeš and White (1972) noted chemical criteria which can be used to determine which of these tectonic environments was responsible for any particular succession. The chemistry of the Duffer Formation is probably closest to that of rocks in the island arc environment, although many of the diagnostic elements are unfortunately those most susceptible to metasomatic redistribution.

The Whim Creek Group has not been sampled, but is known to include basalt, andesite, dacite, rhyolite and volcanogenic sediments. This assembly suggests an island-arc environment of deposition.

MAFIC VOLCANIC ROCKS

About 300 samples of basalt and dolerite have been analysed. No detailed geochemical description of these rocks is presented in this bulletin because statistical treatment and interpretation of the data are still at a preliminary stage. Appendix F gives the mean composition of the six basalt formations investigated so far. Each of the first four columns includes rocks from several traverses.

In view of the large number of samples involved and the widespread geographic and stratigraphic distribution (between Marble Bar, Nullagine and Soanesville) there is good reason to believe that the chemistry of these rocks is representative of all mafic volcanics in the eastern part of the Pilbara Block. About 90% of the rocks are tholeiitic and the remainder consist of komatiites (high MgO) and minor andesite. None of the traverses yielded an abnormal percentage of spilitized rocks (Na_2O is more than 2.5% in 32% of the samples) and carbonatization is not a serious problem (CO_2 exceeds 3.0% in 14% of the samples). Obviously carbonatized rocks were collected only at localities where 'fresh' rocks were unavailable. In most areas, single samples were collected at regular intervals (generally 50 to 200 m) across strike. At some outcrops, several samples were collected to check local chemical variations.

Recent tholeiite piles occur in three principal environments, oceanic, island arc, and continental. Published analyses (Engel and others, 1965; Manson, 1967; Miyashiro and others, 1969; Jakeš and White, 1972; White and others, 1971; Gunn, 1976) indicate that TiO_2, K_2O, P_2O_5 and possibly MgO vary between these environments. Indeed, TiO_2, K_2O and P_2O_5 have been used by Pearce and others (1975) to discriminate between oceanic and non-oceanic basalts.

Three assumptions must be made if these criteria are applied to Archaean rocks: the composition of the mantle has not significantly changed over 3 000 m.y.; alteration has not systematically changed the composition of Archaean basaltic rocks; and Archaean tectonic environments were similar to those of today.

The second assumption is probably valid, providing a large number of Archaean rocks are analysed. There is evidence that the first assumption does not hold with respect to Fe (generally higher in Archaean basalt) and Al (consistently lower in Archaean basalt), but this may not affect the elements under discussion. Many analogies have been drawn between Archaean and Phanerozoic successions, but structures such as granitic domes and intervening greenstone synclines have no close Phanerozoic counterparts (granitic diapirs of the Round Pond area, Newfoundland, and the northwestern Sierra Nevada, California which are referred to by Burke and others (1976), have the appearance of true magmatic intrusions rather than domes produced by upward movement of solid material).

If chemical comparisons of the type mentioned above are made, the basaltic formations of the Warrawoona Group appear to be oceanic in character (high TiO_2 and low K_2O) whereas the Charteris Basalt and the Honeyeater Basalt (Gorge Creek Group) have island-arc or possibly even continental affinities (low TiO_2—not, however, typical of continental tholeiite—and high K_2O). $TiO_2/Zr/Y$ ratios (Pearce and Cann, 1971) indicate an oceanic origin for all six formations, although the Charteris Basalt plots close to the island-arc field.

When trace element concentrations are considered the basaltic formations of the Pilbara Supergroup are 'oceanic' with respect to Cr, Ni and Sr but 'island-arc' with respect to Rb, Ba and Y. In this they are typical of Archaean greenstones elsewhere (Jahn and others, 1974). Tarney (1976) pointed out that Phanerozoic marginal basin basalts most closely resemble Archaean greenstones in that they possess high Cr and Ni coupled with relatively high concentrations of lithophile elements.

Basaltic komatiite (as defined by Viljoen and Viljoen, 1969) occurs in five of the basaltic formations (Appendix G). These rocks have normal SiO_2 contents for basalt but MgO is abnormally high (generally greater than 10.0 per cent, CaO/Al_2O_3 exceeds 1.0 and TiO_2, Na_2O and K_2O are lower than in normal basalt. Peridotitic komatiite occurs near the base of the Apex Basalt at Camel Creek and in the lower part of the Euro Basalt at the Hong Kong mining centre. The fact that these magnesium-rich rocks are not concentrated near the base of the Pilbara Supergroup is evidence that they do not represent part of the most primitive oceanic crust, as has been suggested in South Africa (Viljoen and Viljoen, 1969). In fact, Windley (1977, p. 48) stated that komatiitic rocks occur in Phanerozoic successions in several areas of the world. Peridotitic komatiite such as that at Camel Creek is of considerable interest, however, because it probably represents a 60-80% melt (Green and others, 1975) of the Earth's mantle 3 400 m.y. ago.

CHAPTER 6

Structure and Evolution

INTRODUCTION

The Archaean structural geology of the Pilbara Block is dominated by granitic domes and greenstone synclines (Frontispiece). These structures are unlike folds formed in most Proterozoic and Phanerozoic terrains and appear to have originated through tectonic processes no longer in operation. Noldart and Wyatt (1962) recognized the existence of dome and basin structures and attributed them to cross-folding of an earlier fold system. Late orogenic granitic batholiths were said to have "tightened the existing fold patterns, further compressing the synclinal belts and accentuating the domal patterns". This interpretation is now rejected because there is no evidence of interfering fold systems where greenstone synclines meet and "cross" one another. The main cleavage of the synclines is a subvertical schistosity which passes continuously from one greenstone belt to another, commonly curving through 90° and trending parallel to the nearest granite-greenstone contact. This cleavage can be traced across strike into the marginal areas of the granitic domes, but towards the centres of the domes it weakens and eventually fades out. The domes are essentially diapiric structures whereas the greenstone synclines occupy areas in which the Pilbara Supergroup sank downwards into the granitic substratum. This process is thought to have involved progressive gravity deformation over a long period of time (probably several hundred million years). Some parts of the craton became unstable before others because of regional variations in the thicknessess of the substratum and the Pilbara Supergroup. As a consequence, the domes and synclines commenced development at slightly different times in different areas. The first major unconformity in the Pilbara Supergroup occurs at the base of the Wyman Formation, indicating that significant earth movements and resulting erosion commenced only after deposition of the Euro Basalt. In some areas of the craton no unconformity is present at this stratigraphic level and deformation must have started later.

PHASES OF DEFORMATION

Although the domes and synclines are the largest and most conspicuous structures of the craton, structures belonging to other episodes of deformation have also been recognized. The four Archaean episodes of deformation described by Hickman (1975b) from the Marble Bar and Nullagine Sheet areas are now known to have produced similar structures in other parts of the Pilbara Block. These episodes are summarized as follows:

D1. Interfolding of greenstone and granitic material, granitic intrusion and migmatization.

D2. Main deformation involving diapiric movement of granitic material (essentially solid-state, although syntectonic granites were locally intruded) and downward movement of the surrounding greenstones. Greenschist to amphibolite facies metamorphism.

- D3. Conjugate folding and faulting associated with regional east-west compression. Faults produced by north-south compression (?late stage).
- D4. Tight to open folding about subhorizontal axial planes. Relations to D3 uncertain.

FIRST DEFORMATION, D1

D1 is a convenient term to refer to all types of structures (tectonic and igneous) deformed by D2. These various early structures formed during several events, but present knowledge does not permit a chronological subdivision. They include early isoclinal folds of greenstone material now forming detached structures (e.g. mega-xenoliths) within the batholiths, schistose dykes, gneissic banding, certain pegmatite veins and pre-D2 intrusive contacts.

EARLY ISOCLINAL FOLDS

The granitic batholiths locally contain greenstone xenoliths up to 10 km long and 1 km wide. Many of these masses occupy the synclinal root zones of eroded D2 synclines, but others lie outside the axial areas of these structures. Xenoliths of the latter type locally contain a cleavage, S1, predating the regional schistosity, S2 (e.g. mega-xenoliths in the Garden Creek and Tambourah Creek areas). S1 has not been identified in the main greenstone belts and the implication is that the xenoliths represent pre-Pilbara Supergroup volcanics interfolded or intruded by ancient granitic rocks. Sections of the batholiths which appear to contain these structures have been inadequately examined and far more detailed work is required.

SCHISTOSE DYKES

If, as is postulated, the batholiths include granitic rocks pre-dating the Pilbara Supergroup, and if volcanic rocks of the latter were extruded over all or most of the craton, it is reasonable to expect remnants of mafic and ultramafic feeder dykes in the granitic terrains. Most of the dolerite dykes which intrude the batholiths are massive, undeformed (post—D2) and almost certainly Proterozoic in age (many actually intrude the overlying Proterozoic succession). Less common are sinuous schistose mafic dykes containing rocks metamorphosed to greenschist or amphibolite facies. In the southern part of the Mount Edgar Batholith such dykes are folded by D2 and crossed by S2. Similar dykes occur at Callawa, Abydos and Yandeearra, and many of the smaller mega-xenoliths may also have originated as dykes. Deformation and metamorphism commonly make the distinction between dykes and volcanic sheets stoped from the Pilbara Supergroup, difficult or impossible. Geometry and orientation are useful field criteria, however, because true xenoliths have a lower length/width ratio and are generally oriented parallel to adjacent greenstone belts and parallel or subparallel to S2.

Ultramafic dykes intrude granitic rocks northeast of Eginbah, near Callawa, west of Nimingarra, and east of Pilgangoora. These dykes have undergone static metamorphism, and are generally massive but retain recognizable primary textures. They must represent feeders to sills and dykes in the Pilbara Supergroup because no ultramafic rocks occur in the Proterozoic succession.

GNEISSIC BANDING

Most of the granitic rocks which consist of alternating leucocratic and melanocratic bands are best described as stromatic migmatite. Metamorphism is of low to medium grade, and deformation is confined to simple shear. Gneisses of the type encountered in other shield areas (e.g. Greenland) appear to be rare in the Pilbara. At some localities, however, compositional banding deformed by D2 folds and cross-cut by S2 must have been generated by events prior to the main episode of deformation. About 3 km south-southwest of Wallareenya, S2 is a biotite foliation developed parallel to the axial planes of D2 folds which deforms pre-existing banding and pegmatite veins. Similar structures are exposed 15 km northwest of Wallareenya (Fig. 43).

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Figure 43. Similar folding of banded gneiss 15 km northwest of Wallareenya. A biotite foliation (S2) is developed parallel to the axial planes of these D2 folds

PEGMATITE VEINS

Natural rock pavements of foliated granitic rocks commonly reveal three or four phases of pegmatite intrusion. The earliest pegmatites are generally folded, faulted, boudinaged and cross-cut by S2. Pegmatites of this type may be cut by other less deformed or ptygmatic ones. Later straight pegmatites typically post-date S2, but may themselves be cross-cut by pegmatite veins occupying faults. Detailed local studies could probably relate these structures to successive plutonic and tectonic events. In some areas the pegmatites have fairly consistent trends over tens of kilometres

INTRUSIVE CONTACTS

The main foliation in the granitic rocks is a biotite alignment (S2) produced during doming. Most of the batholiths are composed of several plutons, and the contacts between these are commonly crossed by S2 at moderate or large angles. This establishes that plutonic complexes existed prior to doming.

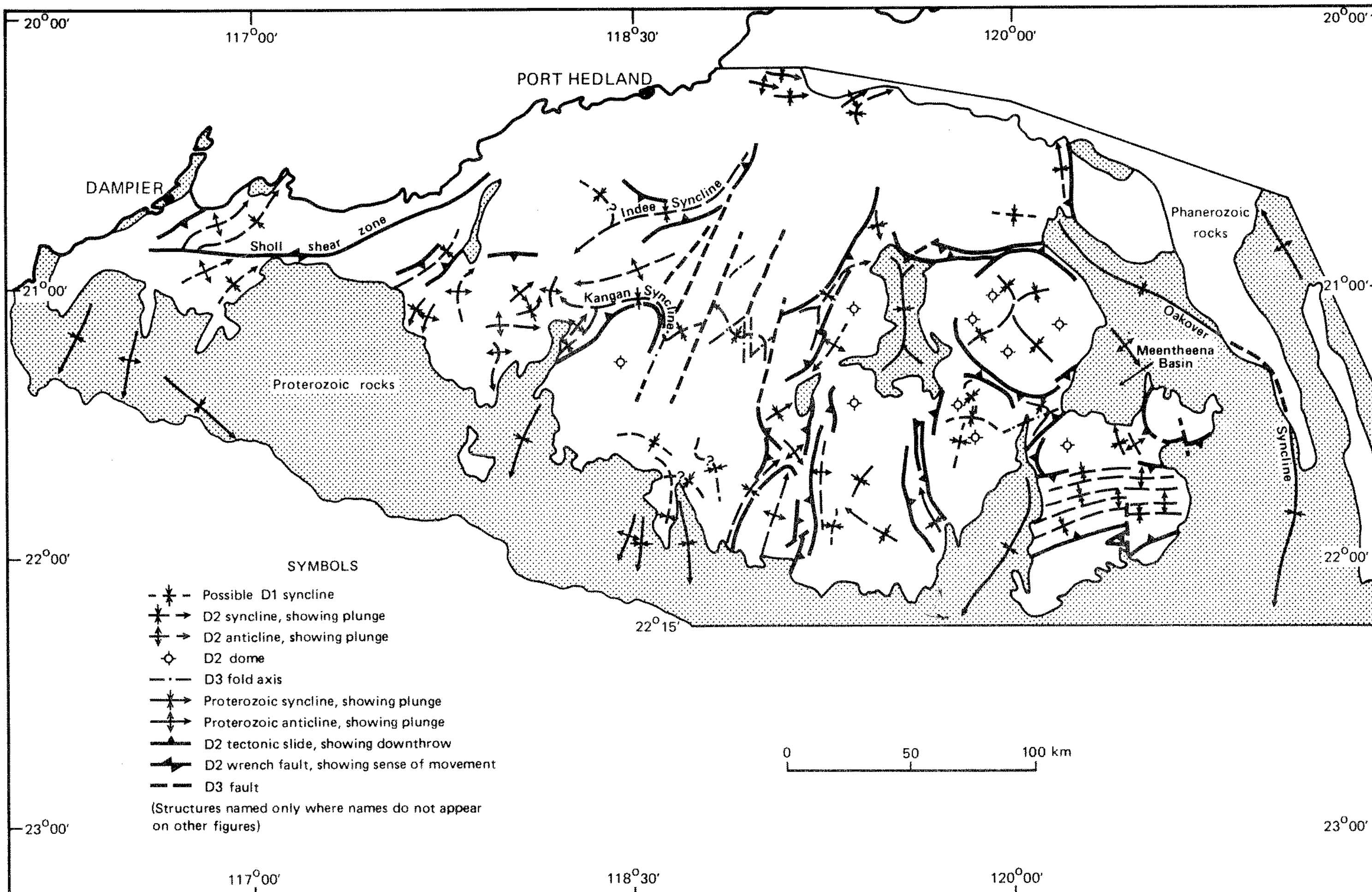

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Figure 44. Principal structures of the Pilbara Block.

MAIN DEFORMATION, D2

The dominant structural elements of the area, the granitic domes and greenstone synclines (Fig. 44), were formed during the main (D2) episode of deformation. At Marble Bar, these structures began to form before deposition of the Duffer Formation (3 500-3 450 m.y.) because a low-angle unconformity separates this unit from the underlying Mount Ada Basalt.

Major crustal movements involving moderate to steep tilting occurred after deposition of the Euro Basalt, which in many areas was eroded before being unconformably overlain by the Wyman Formation. The ages of the Wyman Formation and the overlying Gorge Creek Group have not yet been determined.

Zircon dates suggest that some of the older granitic rocks, which may be genetically related to the Duffer Formation, are about 3 400-3 300 m.y. old. Rb-Sr geochronology indicates a major metamorphic event at 2 950 m.y. (Oversby, 1976), which has 'redated' many of the older granites. This metamorphic event could represent either the pre-Wyman Formation phase of D2 deformation, or the phase following deposition of the Gorge Creek Group. The possibility that D2 in fact encompasses two major tectonic events, one at 2 950 m.y. and one at 2 700-2 600 m.y. (the age of the post-tectonic granites), must be given serious consideration. It is interesting to note that Oversby (1976) recognized a second metamorphic event at 2 770-2 600 m.y. based on Rb-Sr and Pb-Pb mineral isochrons from rocks of the granitic complex.

Noldart and Wyatt (1962) described two events of deformation: the Warrawoona orogeny was said to have predated deposition of the Mosquito Creek Formation and produced the regional dome and syncline structures, and the Mosquito Creek orogeny produced east-west trending folds of the Mosquito Creek Formation. At Mosquito Creek this interpretation satisfactorily explains the situation where dome and syncline structures of the Mount Elsie Belt and the McPhee Dome were quite deeply eroded prior to deposition of the Mosquito Creek Formation. The latter was subsequently deformed by two phases of east-west folding (Hickman, 1975b). To the south of the Mosquito Creek Synclinorium, the Kurrana Batholith is also sheared but no structural effects of this Mosquito Creek phase have been observed elsewhere in the eastern part of the Pilbara Block. This suggests that the deformation was localized, perhaps being confined to depositional basins and underlying granitic basement.

In many parts of the Pilbara, the Wyman Formation and the Gorge Creek Group overlie the older sections of the Pilbara Supergroup without angular discordance, and the entire succession appears to have been folded en masse (e.g. the northern part of the Kelly Belt, the Coongan Syncline, the Lalla Rookh Syncline, the Pilgangoora Syncline, the Soanesville Belt and the Roebourne Syncline). The conclusion must be that the pre-Wyman tectonic event affected only certain areas such as the Budjan Creek section of the Kelly Belt, the Warrawoona Syncline, the Lalla Rookh Syncline (northeastern part), and probably the northern part of the Pilbara Block between and including the Warrawagine Batholith and the Mallina Synclinorium. These areas fall into two major easterly trending zones, one extending from Warrawagine to Mallina, and the other from Mosquito Creek to the southern part of the Kelly Belt and the extreme south of the Coongan Syncline.

Figure 45 illustrates this point and suggests that the pre-Wyman event resulted in the northern and southern margins of the granitic substratum being elevated to form a major U-shaped zone. At these margins, the Warrawoona Group is absent from the succession. In the centre of the 'U' and in the Roebourne-Dampier area the Warrawoona Group is fairly complete and underlies the Wyman Formation conformably or disconformably. Between these two structural zones is a third zone in which the Warrawoona Group was deformed and partly eroded prior to deposition of the Wyman Formation and the Gorge Creek Group.

Figure 45 must be viewed as merely a hypothetical reconstruction because it is uncertain why the Warrawoona Group is absent in some parts of the Pilbara Block. It is possible that the granitic batholiths in the northern part of the craton are considerably younger than the Mount Edgar and Shaw Batholiths, and that the contacts between the granitic rocks and the Gorge Creek Group are intrusive. Alternatively, the Warrawoona Group might have been 'sheared out' on the limbs of the synclines, and may in fact, still underlie them at depth. Shearing and intrusion are locally present, but, as yet, there is no evidence that either occurred on a regional scale. The possibility that the Warrawoona Group was never deposited in this area seems less probably because there is no evidence of lateral stratigraphic thinning.

It will be obvious from the above discussion that the D2 episode of deformation was not a single short-lived event affecting the entire craton at any particular time.

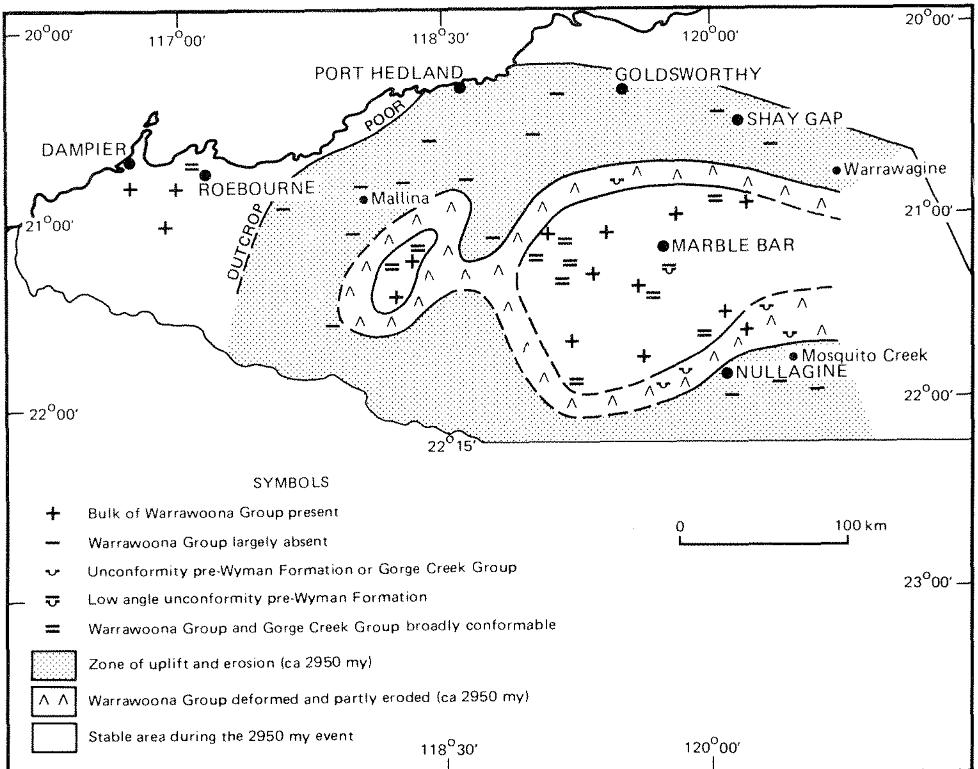

Figure 45. Hypothetical tectonic zones produced by the earliest major phase of D2 deformation (ca. 2 950 m.y.).

Geochronology is required on the Wyman Formation and, perhaps more importantly, on the Gorge Creek Group to establish whether or not they post-date the 2950 m.y. event. If they are found to be younger than 2950 m.y., D2 will require subdivision. At present, however, it is equally possible that D2 consists of numerous local deformations (there are local unconformities in the Gorge Creek Group) occurring at different places, but nevertheless related to a continual process of downwarping and uplift. Accordingly, three distinct phases of tectonism at Mosquito Creek: pre—Mosquito Creek Formation dome and syncline development; tight to isoclinal folding with associated axial-plane cleavage; and tight folding deforming the earlier cleavage are here all grouped under D2.

The D2 fold pattern of broad granitic domes and narrow cuspate synclines containing the Pilbara Supergroup is typical of a buckled basement-supracrustal contact where the basement material is the more viscous (Ramsay, 1967, p. 383-386). Internal deformation styles within the two types of rock are, as might be expected, very different. The synclines contain folds ranging from upright, tight to isoclinal, noncylindrical, nonplanar and conical similar folds. Shearing-out of limbs along tectonic slides is common and results in local tectonic breaks within the succession. Such slides may possess narrow shear zones (perhaps only a few centimetres) and can be difficult to identify.

Some workers (e.g. Burke and others, 1976, p. 124) have suggested that slides duplicate many of the world's greenstone successions, and cause unsuspecting geologists to draw up erroneously thick stratigraphic columns. They suggest that most greenstone successions are less than 10 km in true thickness. In this connection, it should be noted that whereas the maximum total thickness of the Pilbara Supergroup (i.e. the sum of maximum thickness of individual formations) is 30 km, its maximum true thickness in any one area is about 15 km (Plate 2). This discrepancy, however, is not due to tectonic duplication but to stratigraphic wedging, specially of the Duffer Formation and formations belonging to the Gorge Creek Group. Some of the measured sections are relatively flat-lying and contain virtually undeformed rocks. The regional persistence of the succession would require any such undetected slide to occur at the same stratigraphic level in all the greenstone belts. Moreover, the succession is essentially simple, there are no major 'cycles' sufficiently similar to be tectonic duplications. Duplication of most of the units can also be ruled out on geochemical criteria, which go some way towards substituting diagnostic fossils as a tool in stratigraphic correlation (Glikson and Hickman, 1981).

D2 folding of the greenstone belts is accompanied by a cleavage (S2) parallel or subparallel to bedding. It is most strongly developed in steeply inclined strata where a belt is tightly 'squeezed' between adjacent batholiths. Examples include the Warrawoona Syncline, the northern part of the Lalla Rookh Syncline and the Western Shaw Belt. Most of the rocks in such belts are schists; primary igneous textures and structures have been obliterated by the effects of attenuation and shear. The schistosity is an alignment of platy metamorphic minerals such as sericite, chlorite, actinolite, talc, serpentine and secondary quartz. It is not parallel to the axial-plane surfaces of greenstone synclines, but is parallel to belt margins, and appears to be associated with shear closely parallel to bedding. This is an important point since it testifies to differential vertical shear geometrically related to the shape of the granitic batholiths rather than axial-plane cleavage under horizontal compression.

Granite-greenstone contacts are either intrusive or tectonic; in no case has an unconformity been confirmed between granitic rocks and either the Warrawoona or the Gorge Creek Group (an unconformity does exist between the Late Archaean Whim Creek Group and the Caines Well Granite). This situation appears to be very common in Archaean terrains elsewhere in the world, and has often been cited as evidence that the granitic domes are magmatic intrusions.

Marginal intrusive relationships do not of course prove that an entire granitic dome is a magmatic intrusion. As excellently demonstrated by the post-tectonic Mondana Adamellite, granite-greenstone contacts are very susceptible to later intrusion. Moreover, the migmatites of contact zones are sheared in harmony with neighbouring greenstones. Tectonic foliation can often be traced along strike from greenstone rocks across invading granitic bodies and back into greenstones. Clearly the intrusive granites generally pre-date marginal shear. Many of the foliated marginal intrusive bodies are probably syntectonic granitic rocks generated during deformation of the older granitic complex. Such rocks could have originated as intrusions into the mechanically active contact zone during doming, consolidated, and then been sheared by continued deformation. Alternatively, some of the migmatitic marginal granites may have formed before doming by intrusion along the boundary between the granitic substratum and the Pilbara Supergroup.

The granitic domes are broad, steep-sided structures, generally round to ovoid in plan and measuring 30 to 100 km in diameter. Surface geology and Bouguer anomaly patterns indicate that the domes merge beneath the syclinal greenstone belts to form a predominantly granitic basement. At depth, certain of the greenstone belts (e.g. Wodgina Belt) are intruded by syntectonic and post-tectonic granitic intrusions so that they are in fact shallower than the inclinations of their contacts would indicate. Unexpectedly low Bouguer anomalies across many of the other belts suggest that such basal intrusion may be widespread.

The granitic domes are characterized by folding close to the concentric model with flexural slip along shear planes parallel to the granite-greenstone contacts. This shear has resulted in the formation of a tectonic foliation varying from a weak alignment of biotite to a stronger parallel orientation of quartz, sericite and mafic minerals. Extensive shear commonly occurs close to narrow, steeply inclined greenstone belts in which the Pilbara Supergroup shows obvious signs of extreme attenuation. Many kilometres of the greenstone succession has been slid out at certain contacts.

Few of the domes are simple structures; most, especially the large ones, contain synclines in which the mechanical foliation S2 converges downwards. These intradomal synclines are characterized by broken trains of greenstone material and, in some cases, by shear belts along their length. Their rocks and structures are similar to those found near contacts with the major greenstone belts and the probability is that many are root zones of now eroded overlying greenstone synclines. This is the situation at Warrery Gap (Corunna Batholith), Tambourah (Yule Batholith) and Lynas Find (Carlindi Batholith) where tapering greenstone protuberances pass progressively into intradomal synclines as deeper structural levels are exposed.

Many of the batholiths contain post-tectonic granitic intrusions dated at between 2 700 and 2 600 m.y. These intrusions are almost certainly related to the second metamorphic event (2 770-2 600 m.y.) recognized by Oversby (1976). As noted above, future investigations may show that this event marks a period of deformation distinct from the main episode of dome and syncline development, but for the present it is regarded as the final phase of D2.

Unlike the foliated granitic complex, the post-tectonic intrusions are massive and discordant with sharply defined contacts. An absence of marginal disruption of the intruded country rocks and the occurrence of roof pendants and xenoliths of host rocks indicates intrusion by a process of magmatic stoping rather than 'forceful' injection. The post-tectonic intrusions show a tendency to be located within intradomal synclines (e.g. the Moolyella Adamellite and Cookes Creek Granite) or at granite-greenstone contacts (e.g. the Mondana Adamellite). Partial melting of the older granitic complex probably took place preferentially beneath the synclines, because here the granitic substratum was forced deeper into the lithosphere. Strain effects were also far greater in the synclines than in the centres of the domes, which have preserved their primary igneous textures. Following melting, magmatic intrusion would have occurred most readily along zones of weakness such as lithological contacts and shear planes, features mainly located in the synclines.

Major D2 faults occur in some areas. The Sholl Shear Zone is a major crustal dislocation extending 140 km from Peawah Hill to Mount Prinsep. Between Mount Prinsep and Andover, and at Balla Balla, the shear zone varies up to 1 km in width and contains cataclastic schist veined by quartz. Movement indicators such as slickensides have not been observed, but the outcrop pattern of the Roebourne-Mount Sholl area indicates an effective sinistral displacement of 20-30 km. Several strike faults complicate the structure of the Whim Creek Belt. Here movement appears to be largely vertical, but its magnitude and sense is generally uncertain. At Pilbara Well a tectonic slide partly replaces the northwestern limb of a major isoclincal anticline. The existence of an anticline at this locality was first recognized by Fitton and others (1975), although the writer has since slightly modified their original structural interpretation.

Important D2 faults occur on both limbs of the Lalla Rookh Syncline. These take the form of tectonic slides, a core of isoclinally folded sandstone being rifted downwards into rocks of the Warrawoona Group. A major D2 dislocation (the Garden Creek Slide) occurs on the eastern margin of the Western Shaw Belt, and related slides are evident between Tambina Creek and Dalton Creek. The Garden Creek Slide strikes north over a distance of 45 km, and is inclined westwards at 70-80 degrees; it replaces almost the entire eastern limb of a syncline forming the Western Shaw Belt. Similar slides occur at the southern margin of the Muccan Batholith, the southern margin of the Mount Edgar Batholith, the northern margin of the Corunna Downs Batholith, the western and southern margins of the Yilgalong Granite and on the southern margin of the Mosquito Creek Synclinorium. All these structures were produced by upward movement of granitic masses relative to the Pilbara Supergroup.

A somewhat different fault structure extends from Bamboo Creek mining centre to Pear Creek. From Bamboo Creek to Doolena Gap it is an arcuate normal fault related to the Mount Edgar Batholith. Farther west it is replaced by a fault related to the Muccan Batholith. Along most of its length the fault is intruded by peridotite (now serpentinite), which appears to contain abnormally high nickel and chromium (approximately twice the average value for this type of rock elsewhere in the Pilbara). The presence of a structurally controlled ultramafic intrusion indicates that this fracture may have extended to the mantle. Metaperidotites also occupy faults along the southern and northern margins of the Mosquito Creek Synclinorium, a slide at the southern margin of the Yilgalong Granite, an east-striking fracture within the Pilgangoora Syncline, and sections of the Sholl Shear Zone. Serpentinite bodies on the southeastern limb of the Indee Syncline, the northern limb of the Kangan Syncline and the western limb of the Wodgina Belt may also intrude faults.

In the preceding pages considerable emphasis has been placed on the role of vertical movements during D2 deformation. Many previous workers in Archaean granite-greenstone terrain have expressed the view that domes and synclines are the result of vertically acting forces, either through gravitational downwarping or upward injection of diapiric granites. Burke and others (1976) criticized these interpretations, and argued that rapid horizontal movements are responsible for the structures. The deformation is said to have involved collisions between island-arc systems and microcontinental masses during sea-floor spreading, subduction and continental drift. Burke and others (1976, p. 117) stated that the tectonic environment responsible for typical granite-greenstone terrains is compatible with plate tectonics, citing a 2 100-1 800 m.y. example in West Africa. Lenticular patterns in the granite-greenstone terrain are said to result from a complex series of events involving either relative plate motion or significant horizontal shortening with consequent upward motion of material to compensate (Burke and others, 1976, p. 121-122). They comment that ". . . the supposed vertical tectonic style reported from greenstone belts seems to be based on the alleged control of deformation by the silicic plutons, the alleged simple synclinal structures of the belts and, perhaps, on the subvertical elongation lineation commonly observed." Ramsay (1963) is quoted as having shown that the silicic diapirs do not significantly control the deformation in the Barberton greenstone belt of South Africa and the simple synclinal nature of greenstone belts is a myth. Moreover, they argue ". . . it is difficult to see how a strong regional cleavage and associated horizontal shortening could be impressed on relatively hard, cold volcanics and sediments by soft, mushy granitoid diapirs."

Evidence from the Pilbara Block establishes that the granitic batholiths of this craton are the product of solid-state doming (Hickman, 1975b). During D2, the granitic rocks were more competent than the volcanics and sediments of the Pilbara Supergroup. Many of the domes are rimmed by circular normal faults which merely represent an obvious manifestation of the overall shear system; shear is generally present on a microscopic scale. Horizontal compression might produce lenticular domes and synclines of the type present in parts of the Yilgarn Block, but the fact that the Pilbara domes are circular and that there is no regional tectonic trend precludes formation through a single horizontal compression. The absence of interference structures rules out refolding so that horizontal stress fields of more than one orientation cannot be invoked.

Vertical movement is predominant in the formation of the Pilbara diapiric structures, but the cause of this movement is more debatable. The tabular nature of the Warrawoona Group rules out downwarping under narrow elongate geosynclinal basins (a model once adopted by Anhaeusser and others (1968) in the Barberton Mountain Land), but gravity deformation of a different type provides a more satisfactory explanation. Dome and syncline development was probably a response to ". . . inverted density stratification . . ." (Ramberg, 1967), a low density layer (granitic complex) being overlain by a 10-14 km thick high density layer (chiefly basaltic volcanics of the Warrawoona Group). During deformation of the Gorge Creek Group, the supracrustal succession was even thicker, and instability must have been proportionally greater. Upward movement of the broad viscous granitic domes over relatively large areas was accompanied by more rapid downward movement of the less viscous greenstone material in narrow belts. Ramberg's (1967, and *in* Newall and Rast, 1970, p. 261-286) centrifuged models used "low" viscosity, low density bottom layers, and consequently produced structurally discordant salt-dome-like diapirs. In one of his models (S 226), however, equal viscosities were used to produce structures more closely resembling those of the granitic domes and greenstone synclines. Ramberg (1970) concluded, ". . . the experimental results strongly suggest that large domes and batholiths did not rise as magmas chiefly consisting of a liquid portion. The shape of such plutons indicates a moderate viscosity contrast between the rising body and the surroundings, as can be expected between crystalline rocks of unlike composition. Even obsidian glass would be too fluid relative to the surrounding crystalline rocks to expand the bulky shape of many acidic plutons."

The spatial arrangement of the granitic domes was probably influenced by irregularities in the surface of the granitic substratum and/or lateral lithological and thickness variations in the volcanic pile. At Marble Bar, for example, the Duffer Formation wedges out northwards and southwards and is immediately underlain by granitic rocks representing a possible magmatic source region. This inhomogeneity may have promoted the later development of the Mount Edgar Batholith.

THIRD DEFORMATION, D3

In many areas, D2 structures are visibly deformed by folds, faults and cleavage belonging to a later (D3) episode of deformation. Major (D3) folds occur in the Pilgangoora Syncline, Kelly Belt, Wodgina Belt and, to a lesser extent, in the Mosquito Creek Synclinorium and the Western Shaw Belt. The D2 synclinal core of the Pilgangoora Belt is rotated clockwise and anticlockwise by two major D3 conjugate folds between Pincunah and the headwaters of Honeyeater Creek. These folds possess four axes, two trending north-northwest and two trending northeast. The Kelly Belt represents the western limb of a major D2 syncline. In the area of the headwaters of Yandicoogina Creek, the axis of this fold is rotated through 90° by a D3 antiform which plunges steeply northwest. Large D3 folds at Mosquito Creek are illustrated by Hickman (1975b, Fig. 39); the axes of these structures trend north or north-northeast and northwest or west.

Minor D3 conjugate folds (Fig. 46), kink folds and kink bands (Fig. 47) are numerous in the Mosquito Creek, the Pilgangoora and the Goldsworthy Synclines and at Whim Creek, and occur in most areas where Archaean sedimentary rocks, including banded iron-formation, are steeply inclined and strike westerly. Conjugate folds and kink folds are produced where the maximum compressive stress is roughly parallel to the strike of a pre-existing foliation. The latter is commonly bedding, but can also be cleavage. Strain takes the form of brittle failure on two inclined shear planes. In the Pilbara Block D3 dextral shear planes are vertical to steeply inclined and strike northeasterly whereas sinistral shear planes are also steeply inclined but trend northwesterly. The orientation and plunge of the D3 folds is partly governed by the pre-existing fabric but the intersection of their axial planes is the tectonic "b" axis; this axis almost invariably plunges steeply. These various features indicate that the D3 folds formed under a horizontal or subhorizontal maximum compressive stress oriented approximately east-west.

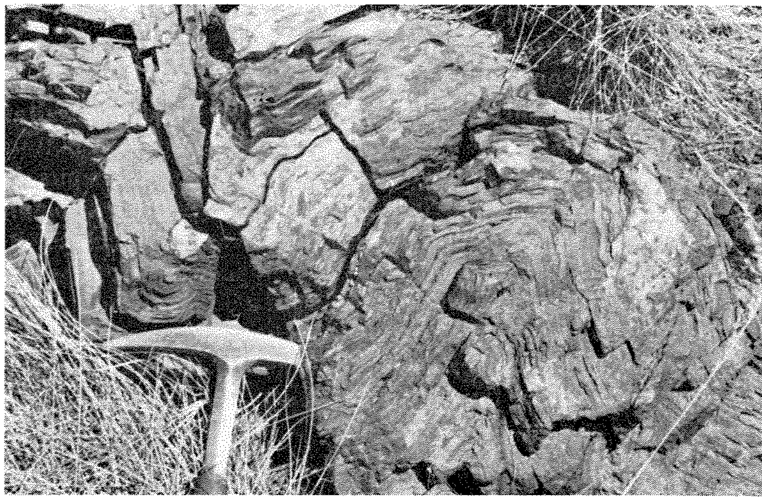

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Figure 46. Conjugate folds in the Cleaverville Formation, 5 km west-northwest of Goldsworthy.

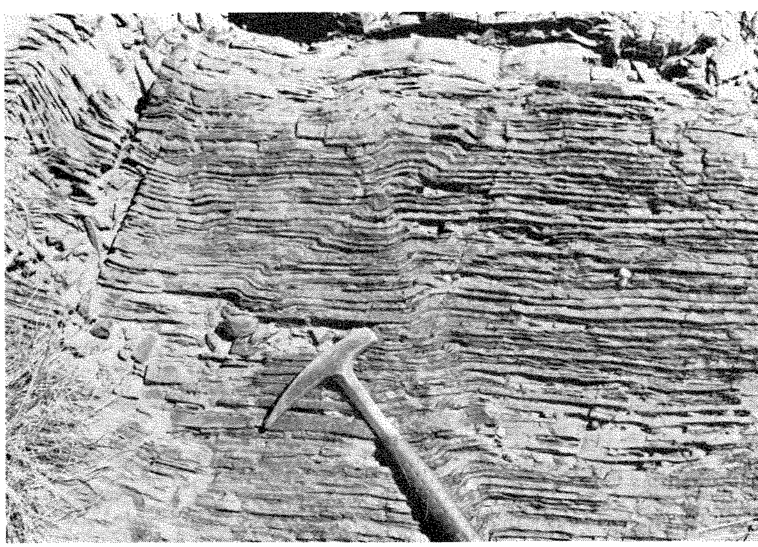

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Figure 47. Conjugate kink bands in the Cleaverville Formation, 5 km west-northwest of Goldsworthy.

A steeply plunging microscopic crenulation of S2 accompanied by a crenulation cleavage (S3) is developed in areas of D3 folding. This cleavage is oriented parallel to the axial surfaces of the folds.

Faults, commonly veined by quartz, are an extremely common D3 structure and fall into two sets, one striking northeast, the other northwest. Most of these faults are wrenches (lateral displacement predominant), but the sense of movement is variable indicating that they formed in two stress fields, one in which maximum compression was directed east-west and the other, north-south.

Dolerite dykes have intruded many D3 fractures and are little deformed by subsequent movement. They cross-cut the post-tectonic granites and were probably feeders for the Lower Proterozoic Fortescue Group. Structures grouped under D3 consequently range in age from late Archaean to Proterozoic.

FOURTH DEFORMATION, D4

Angular subhorizontal D4 folds deform S2 and bedding in some parts of the Pilbara Block. Their axes trend east and their axial surfaces are also subhorizontal so that the folds are essentially recumbent. The folds are tight to open and no isoclines have been observed. Good examples of D4 folds occur in the Ord Range (Blockley, 1976) where they have influenced the development of crocidolite bands. Corrugations on a smaller scale occur in felsic schist at Yandicoogina. The style of D4 folding is distinctive, but its distribution is too localized to make it possible to determine its relations to D3. D4 folds have not been identified in the Mosquito Creek Synclinorium and consequently they may be related to the second east-west trending fold system of that area.

PROTEROZOIC DEFORMATION

The Proterozoic succession is deformed by major open folds possessing no overall regional trend. The most prominent structures are synclines and basins which, as noted by Kriewaldt (1964b), tend to be positioned over Archaean synclines. The latter were probably reactivated after deposition of the Fortescue and Hamersley Groups, but part of the deformation may be due to gravitational downwarping. Stratigraphic features of the Fortescue Group establish that the synclines and structural basins are developed in the same positions as the earliest Proterozoic depositional basins. Consequently they contain the thickest successions.

It must be noted that not all Proterozoic folds were influenced by underlying Archaean structures. Northerly trending open folds occur along the length of the Chichester Range, for example, and the Oakover Syncline and the Meentheena Basin are separated by a northwest trending anticline which crosses a depositional basin. Deformation in the Gregory Range is the product of essentially west-southwest compression involving tight to isoclinal folding about north-northwest axes. Associated high-angle reverse faults (east side up) take the place of some fold limbs.

Rb-Sr and Pb-Pb isotope analyses indicate Proterozoic metamorphic events at about 2 200 m.y. (Oversby, 1976) and 1 200 m.y. (de Laeter and others, 1977). The 2 200 m.y. event (also noted by Leggo and others, 1965) was recognized from mineral isochrons involving the Archaean granitic complex. It is probably significant that two large Proterozoic felsic intrusions have yielded dates close to 2 200 m.y.; these are the Gidley Granophyre which was dated at 2 196 ± 26 m.y. (de Laeter and Trendall, 1971) and the Spinaway Porphyry which was dated at 2 124 ± 195 m.y. (Trendall, 1975b). Dolerite sills which intrude the Weeli Wolli Formation (Hamersley Group) were dated at 2 200 m.y. (de Laeter and others, 1974). Compston and Arriens (1968) dated pisolitic tuff from the Fortescue Group at 2 200 m.y. and acid igneous rocks from the Jeerinah Formation at 2 190 ± 100 m.y. Compston and Arriens (1968) obtained slightly younger ages for acid igneous rocks within the Wyloo Group (2 020 ± 165 m.y.) and the Woongarra Volcanics (2 000 m.y. ± 100 m.y.). For several years these various dates were taken as evidence that the Hamersley Group was deposited about 2 200 m.y. ago, but subsequent geochronology (partly unpublished) now indicates that the true age of the Hamersley and Fortescue Groups lies between 2 600 and 2 300 m.y.

The question now arises whether Proterozoic folding occurred during the events at 2 200 m.y., 1 200 m.y. or both. From the base upwards, the first marked angular unconformity in the Proterozoic succession occurs between the Carawine Dolomite and the Pinjian Chert Breccia. In the Gregory Range, the latter is unconformably overlain by the Waltha Woora Formation. This establishes that the Fortescue and Hamersley Groups were deformed prior to the deposition of the Waltha Woora Formation. The precise age of the Waltha Woora Formation remains uncertain (see Chapter 3), but in the Ragged Hills-Mount Sydney area is is deformed by upright tight to isoclinal folds. These north-northwest-striking structures also deform the Fortescue and Hamersley Groups, in parts of which the structures are accompanied by a well-developed axial-plane cleavage. In the southern part of the Gregory Range, this cleavage possesses the same orientation and general inclination as cleavage within the Gregory Granitic Complex; it is probable that they are the same cleavage. Granitic rocks from Lookout Rocks were dated by de Laeter and others (1977) at 2 650 m.y. A later metamorphic event at 1 200 m.y. was recognized on the basis of a biotite isochron. Thus, Archaean granitic rocks, the Fortescue and Hamersley Groups, and the Waltha Woora Formation may have undergone deformation at about 1 200 m.y. In summary, at least two phases of deformation, probably occurring at 2 200 m.y. and 1 200 m.y. have affected the area's Proterozoic succession.

GEOLOGICAL EVOLUTION

Evolutionary models proposed to explain the origin of granite-greenstone terrains in other areas of the world are too numerous to describe here, but excellent summaries have already been published (e.g. Anhaeusser, 1973; Glikson, 1976a; Windley, 1976, 1977). The models fall into five categories:

(1) geosynclinal (e.g. Anhaeusser and others, 1969), in which the greenstones originated as ophiolite, molasse and flysch deposits in narrow elongate basins on, or adjacent to, pre-existing sialic crust;

(2) oceanic (e.g. Glikson, 1972b), in which the lower stratigraphic units of greenstone belts are seen as remnants of primitive oceanic crust (mafic to ultramafic);

(3) extra-terrestial (e.g. Green, 1972), in which greenstone belts are thought to have originated as equivalents of lunar maria (i.e. by meteoritic impact);

(4) rift-zone (e.g. Windley, 1973), in which greenstone successions accumulated in elongate ensialic or oceanic basins; and

(5) plate tectonic (e.g. Goodwin and Ridler, 1970), in which greenstone successions are compared to those of island arcs and/or marginal basins.

In categories 1-3 the synclinal structure of greenstone belts results from gravitational downwarping but in the plate tectonic models it is a consequence of horizontal movements.

Stratigraphic, geochemical, and structural evidence presented in this and previous chapters exerts certain constraints on any model proposed to explain the geological evolution of the Pilbara Block.

STRATIGRAPHIC EVIDENCE

The stratigraphic succession of the Warrawoona Group is tabular and extends over an area of at least 60 000 km^2. Individual formations can be traced continuously between some of the greenstone belts, establishing that the major synclines are entirely tectonic in origin and bear no direct relationship to depositional basins. The converse relationship, that there is no thinning of the greenstone sequence between synclines, is firmly established at North Pole and McPhee Creek where the Warrawoona Group maintains its normal thickness over large domes. The culmination of the North Pole Dome is eroded to expose part of the underlying granitic substratum (North Pole Adamellite) which, though intrusive and only weakly foliated, petrographically and geochemically resembles the pre- and syntectonic rocks forming the domal batholiths.

The tabular nature of the Warrawoona Group rules out deposition in geosynclines located in the present positions of the greenstone belts. This conclusion is supported by detailed examinations of individual belts which reveal no evidence of facies changes or primary stratigraphic thinning towards syncline margins. Where attenuation is present, it is accompanied by such features as deformed pillows and development of schistosity, indicating its tectonic origin.

The widespread distribution of the Warrawoona Group also precludes any model involving migrating depositories; many of the proponents of island arc and marginal basin models have suggested such a process to explain broadly parallel greenstone belts separated by granitic terrain (as in the Yilgarn Block and the Canadian Shield).

It should be noted that while there is no evidence for more than one depositional basin during accumulation of the Warrawoona Group, separate basins may have developed during deposition of the Lalla Rookh Sandstone and the Mosquito Creek Formation.

Siltstone at the top of the Mount Ada Basalt north of McPhee Reward mine and sandstone units in the Salgash Subgroup at Salgash suggest the existence of an early granitic basement. Granitic pebbles which occur in the Gorge Creek Group southwest of Doolena mine establish active erosion of granitic rocks during deposition of this unit. The age of the Gorge Creek Group is uncertain, but it is isoclinally folded and probably pre-dates the main episode of doming.

Indirect evidence for a pre-Pilbara Supergroup granitic crust is provided by pillow structures in the North Star Basalt. Pillow basalt indicates that surface temperatures were less than 100° C. Several workers have suggested that Archaean geothermal gradients were abnormally high, but Burke and others (1976) have pointed out that if this were the case the basal sections of 10-15 km thick greenstone piles would show effects of high grade metamorphism. This is not the situation in the Pilbara, and it must be assumed that the North Star Basalt was deposited on a crust which was at least 10 km thick and possibly considerably thicker. It is improbable that this crust was basaltic or ultramafic because no large remnants of such a layer are preserved at the base of the Warrawoona Group or within the older complex. If it were granitic, however, it could now form part of the older granitic complex.

Sedimentological evidence (Dunlop, 1978; Barley, 1978; Barley and others, 1979) and palaeontological evidence (Dunlop, 1976; Dunlop and others, 1978; Walter, 1978; Walter and others, 1980; Lowe, 1980) indicates that a large part of the Warrawoona Group was deposited in shallow water. In fact, silica and barite pseudomorphs after gypsum (Barley and others, 1979) testify to evaporitic conditions during deposition of the Towers Formation. This evidence militates against an oceanic model, but is compatible with continental, continental-margin or island-arc environments. Because thick accumulations of clastic sediment are absent in the Warrawoona Group, Barley and others (1979) concluded that adjacent land must have had subdued relief. Influx of detritus would also be governed by climate and distance from source.

GEOCHEMICAL EVIDENCE

The previous chapter presents geochemical evidence that the basaltic formations of the Warrawoona Group most closely resemble the marginal basin type, that they were derived by partial melting of the mantle, and extruded onto a relatively thin sialic crust. In many respects they are chemically similar to oceanic tholeiite, but lithophile elements, such as Rb, Ba and Y, are more concentrated than is normal in this type of rock; it must be stressed that this interpretation is provisional.

The chemistry of the dacitic Duffer and Panorama Formations and of the foliated granitic complex can be explained by partial melting of mafic rocks, extensive remelting of tonalite and granodiorite, or direct derivation from the mantle. The fact that the lowest part of the Duffer Formation is andesitic and that there is no obvious transition from the underlying Mount Ada Basalt casts doubt on a mantle source for this unit, however. The two volcanic units are locally separated by metasediments, including banded iron-formation, which further militates against the Duffer Formation being the upper part of a mafic-felsic cycle. The wedge shaped geometry of the dacitic formations indicates extrusion at local volcanic centres (Marble Bar, Copper Hills, McPhee Creek and Mount Sholl). These centres may have been positioned in areas of early (3 450 m.y.) subduction or downwarping, or at points where the geothermal gradient suddenly increased.

STRUCTURAL EVIDENCE

The granitic domes were formed by upward movement of a solid, granitic substratum, which prior to deformation was a plutonic complex of gneissic, migmatitic and porphyritic rocks. Marginal intrusive relationships reflect syntectonic intrusion along mechanically active granite-greenstone contacts, and do not constitute proof that the domes are magmatic diapirs. Unless the entire foliated granitic complex formed during accumulation of the Pilbara Supergroup, part of it must have constituted a pre-greenstone basement.

The foliated complex may include rocks derived by partial melting of the Warrawoona Group, but the volume of the granitic rocks is far too great for it to have entirely originated in this way. The maximum original volume of basaltic and ultramafic rocks in the Warrawoona Group is estimated at 4.8×10^5 km^3 (8 km thick x 6.0×10^4 km^2 area of Pilbara Block). Of this, less than half, say 2.0×10^5 km^2, is absent from the present succession. Partial melting of this material might have yielded 5.0×10^4 km^3 of granodiorite, but the volume of the foliated complex now exceeds 9.0×10^5 km^3 (30 km estimated depth, 2.0×10^4 km^2 area of outcrop). These figures are approximate, but establish that the bulk of the foliated complex must be derived either directly from the mantle or by remelting of pre-Warrawoona Group crustal material.

STAGES OF DEVELOPMENT

(1) 4 600-3 900 m.y.

Formation of a protocrust occurred through processes of core formation, mantle differentiation and meteoritic bombardment. The composition of the protocrust is uncertain because no remnants of it have yet been identified. Theoretical geology and lunar studies, however, suggest that it included basaltic, anorthositic and granitic rocks. The earliest crust must have been mafic (Murthy, 1976), but subsequent fractionation could have produced a 10-15 km thick granitic layer (Shaw, 1976). This crust was unstable and successive periods of remelting, volcanism, crystallization and annealing, coupled with locally catastropic effects of meteoritic impact, must have produced a complex sialic (quartz diorite-granodiorite) layer containing enclaves of metabasalt.

(2) 3 900-3 600 m.y.

The existence of 3 800 m.y. granitic, volcanic and sedimentary rocks in Greenland and Minnesota establishes that greenstone-belt-type volcanism, sedimentation and granitic intrusion could have preceded deposition of the Pilbara Supergroup. Relics of rocks formed at this time may be included in the mega-xenoliths and gneissic rocks of the batholiths.

(3) ca. 3 600 m.y.

Tholeiitic basaltic rocks (Talga Talga Subgroup) were extruded (partly subaqueously) over all, or a large part of, the area of the Pilbara Block (Fig. 48). Thin sedimentary and rhyolitic units could have been derived by erosion and partial melting of the granitic crust.

(4) 3 550-3 450 m.y.

Local deformation was followed by the development of calk-alkaline volcanic centres (Duffer Formation). Contemporaneous intrusion of granodiorite into the underlying sialic crust and the Talga Talga Subgroup probably occurred at this time.

(5) Post-3 450, pre-2 950 m.y. (probably ca.3 400 m.y.)

Stable conditions prevailed during which time a 4 km thick tabular succession of pillow tholeiite, komatiite and chert units (Salgash Subgroup) was deposited over the Pilbara Block. The basal part of the succession may have included evaporites and fossiliferous carbonate units (Dunlop and others, 1978). Felsic volcanism with associated deposition of chert and volcanogenic sediments (including local conglomerate) interrupted the accumulation of the basaltic pile in most areas (e.g. Panorama Ridge, Shaw Gorge and Kelly mine).

(6a) 3 400-2 950 m.y.

Domes and synclines developed in response to inverted density stratification. Deformation and upward diapiric movement of the granitic substratum appears to have been most extensive in an 80 km wide zone between Warrawagine and Mallina, and in an east-west zone south of Mosquito Creek and Kelly. In these areas, the bulk of the Warrawoona Group was eroded prior to deposition of the Wyman Formation and the overlying Gorge Creek Group.

(b) Partial melting of the granitic substratum resulted in extrusion of rhyolite (Wyman Formation). Erosion of the uplifted granitic substratum and folded sections of the Warrawoona Group continued to

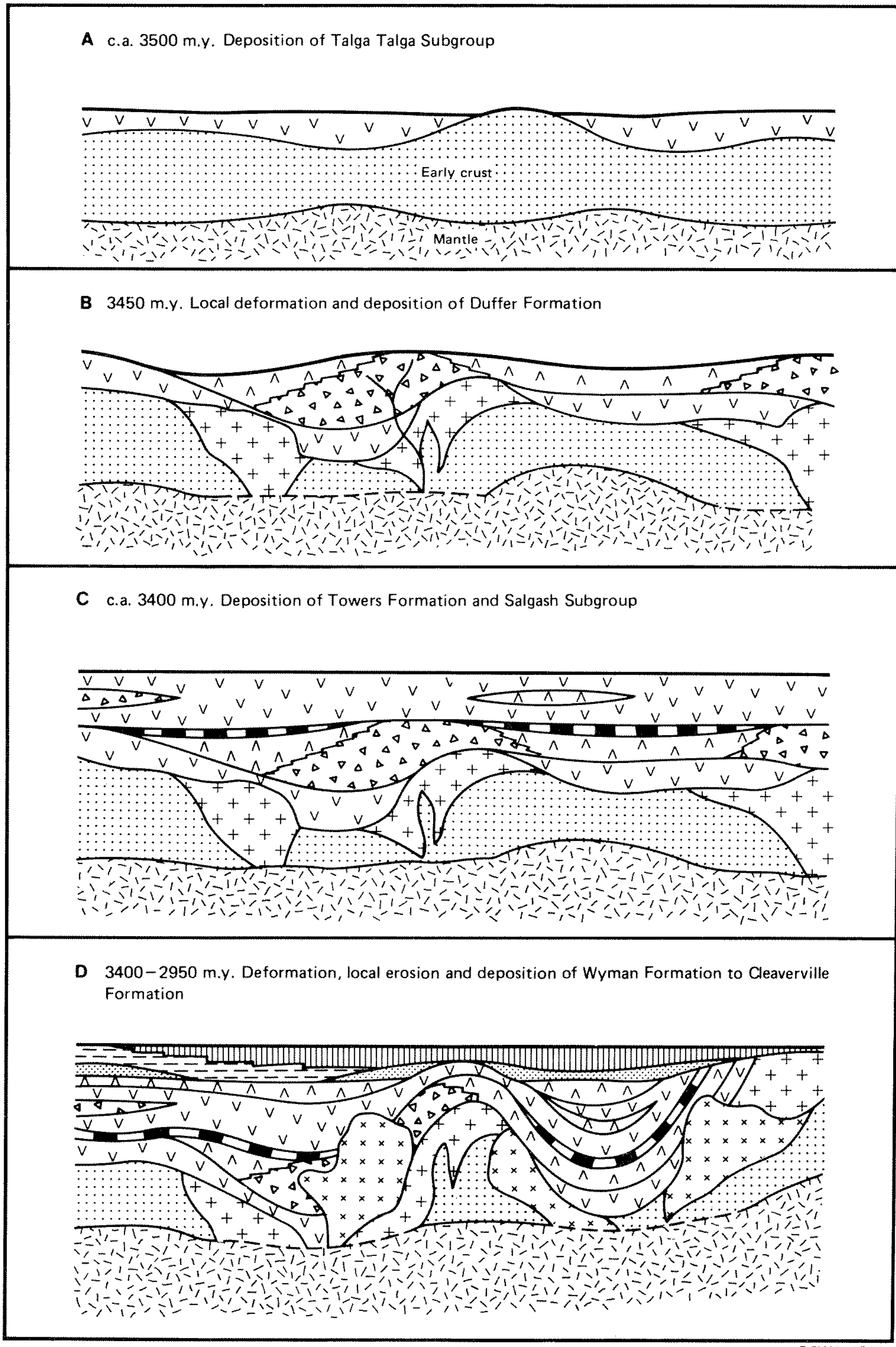
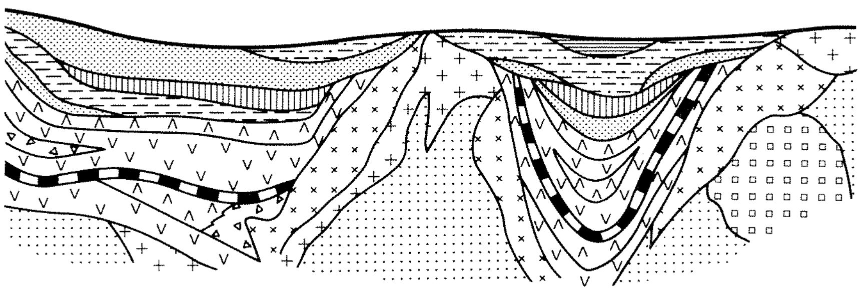
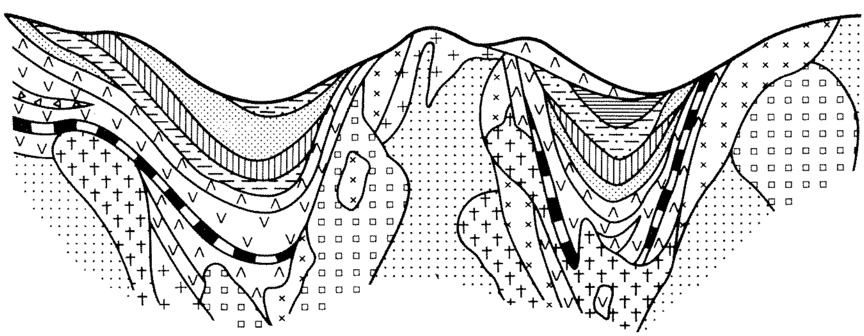


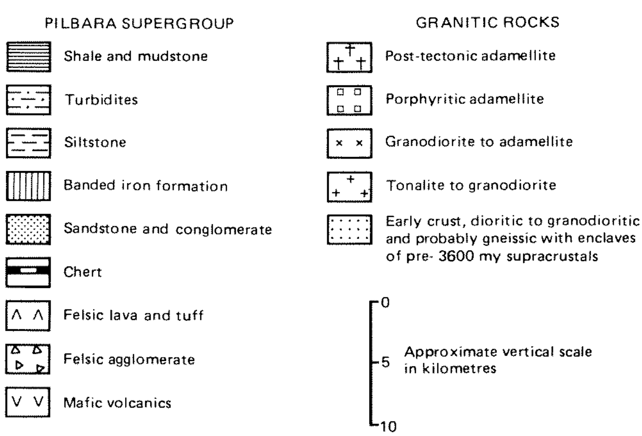
Figure 48. Stages in the evolution of the Pilbara Supergroup.

E c.a. 2950 m.y. Deformation, local erosion and deposition of Lalla Rookh Sandstone and Mosquito Creek Formation. Major deformation.



F 2700-2600 m.y. Deformation, erosion and deposition of Whim Creek Group





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produce widespread deposition of sandstone, shale and local turbidites (Corboy Formation and Soanesville Subgroup) outside the uplifted zones (chiefly in the area between Gorge Creek, Coppin Gap, Cookes Creek and Soanesville).

(c) Peneplanation was followed by submergence and deposition of banded iron-formation (Cleaverville Formation) across the greater part of the Pilbara Block.

(d) Deformation recommenced and large areas of granitic terrain were again exposed to erosion. In certain areas (e.g. Pilbara Well) the Cleaverville Formation was also eroded (Fitton and others, 1975). Considerable thicknesses (up to 5 km) of quartzofeldspathic sandstone, grit and conglomerate (Lalla Rookh Sandstone) were deposited in basin areas between Croydon, Shay Gap, Budjan Creek and Eastern Creek. Rapid downwarping occurred in a northeast trending basin between Nunyerry and Port Hedland and in an east-northeast trending basin between Eastern Creek and Bonney Downs. Here, basal sandstone units pass upwards into turbidite sequences up to 5 km thick; these now form the Mallina and Mosquito Creek Formations.

(7) 2 950 m.y.

Infilling of the Gorge Creek Group basins was followed by a major episode of deformation that completed the development of most of the dome and syncline structures. In the absence of isotopic evidence to the contrary, the age of this deformation is currently believed to be 2 950 m.y. (the main metamorphic event recognized by Oversby, 1976).

(8) 2 950-2 600 m.y.

Erosion of uplifted areas was followed by the intrusion of post-tectonic potassic granite and adamellite plutons between 2 700 and 2 600 m.y. At Whim Creek and possibly in some other areas (e.g. northwest of Soanesville) there were local volcanic eruptions and deposition of volcanogenic sediments (Whim Creek Group) with associated intrusion of granite and dacite porphyry.

(9) 2 700-2 600 m.y.

Open folding and strike-faulting in the Whim Creek area was followed by erosion and the extrusion of basalt and andesite (Negri Volcanics). The widespread D3 episode of deformation occurred in response to east-west compression at about this time.

(10) 2 600-2 200 m.y. (Proterozoic era).

Erosion of the Pilbara Block continued and the Fortescue and Hamersley Groups were deposited.

(11) 2 200 m.y.

Open folding of the Proterozoic succession was accompanied by local tightening of underlying Archaean structures.

(12) Erosion was followed by deposition of the Middle Proterozoic Pinjian Chert Breccia. Local deformation followed this event and the Waltha Woora Formation and the Yeneena Group were deposited.

(13) 1 200 m.y.

Extensive deformation and associated low-grade metamorphism occurred in the Gregory Range Area.

It should be noted that whereas the sequence of events listed above is fairly firmly established, their absolute age is less certain. This comment applies especially to stages 3, 5, 6b-7, 11, 12, and 13.

CHAPTER 7

Economic Geology

For administrative and statistical purposes the auriferous areas of Western Australia are divided into Goldfields, and these in turn are subdivided into Districts (the boundaries of the Goldfields and Districts rarely have any geological significance).

The Pilbara Block occupies the western part of the Pilbara Goldfield and the northern part of the West Pilbara Goldfield. The Pilbara Goldfield is further subdivided into the Marble Bar and Nullagine Districts.

GOLD

Gold was first reliably recorded from the Pilbara Block in 1877 at Roebourne (Maitland, 1909). Total recorded gold production to the end of 1977 stood at 17 601.4 kg (Table 7).

The gold deposits can be classified into six principal types:

Quartz veins in Archaean volcanic and ultramafic rocks;
Quartz veins in Archaean sedimentary rocks;
Quartz veins in Archaean granitic rocks;
Quartz veins in Archaean quartz-feldspar porphyry;
Proterozoic conglomerate deposits;
Cainozoic alluvial-colluvial deposits.

Most of the gold mined occurs in native form, but is invariably alloyed with silver and, in some cases, other metals. The proportion of silver is usually 5 to 15 % but varies from one deposit to another: the Bobby Dazzler nugget (from Shark mining centre) contained 23.04 % silver, whereas the Friendly Creek nugget (Pilbara mining centre) assayed only 6.00 % silver. Grains of gold range in size from microscopic particles to nuggets (e.g. the Bobby Dazzler weighed 15.15 kg, or 487 oz) and measured about 300 mm in diameter (it should be noted, however, that many of the larger nuggets represent concentrations produced by stream action on larger, less pure masses).

In some primary deposits gold occurs as very small specks included in other metal sulphides; complete recovery of such gold is difficult and expense may be prohibitive. Most of the gold obtained from the area has been mined from supergene enrichments in quartz veins which intrude the Archaean layered succession. The quartz veins are generally between 0.3 m and 2 m wide, subvertical and up to several kilometres in length. They are concentrated in the more deformed and metamorphosed parts of the greenstone belts and commonly occupy strike faults. The general parallelism of quartz veins with adjacent strata and/or principal tectonic foliation is a notable feature of the deposits. Many of the veins occur close to intrusive granitic masses and are probably of hydrothermal origin, but others appear to be metamorphic segregations formed during the main episode of deformation. In both types of vein the gold was probably derived from adjacent volcanic and sedimentary rocks.

The primary gold content of hydrothermal quartz veins is far lower than that in the auriferous deposits. The general concentration level of gold in granitic rocks is about 0.01 to 0.001 ppm (Jones, 1969) and pegmatite contains less than 0.01 ppm so that the element is unlikely to have been entirely derived from a granitic magma. Tilling and others (1973) comment that gold becomes depleted in the residual silicate melt in differentiating calc-alkalic magmas. Gold contents of basaltic rocks are also low, but ultramafic and gabbroic rocks do possess somewhat higher values (up to about 0.02 ppm). Precipitation of ore-grade concentrations of gold by thermal waters (associated with volcanism) low in gold (0.05 ppb or less) that have circulated through a rock also low in gold is possible in a long-lived hydrothermal system, e.g. the Yellowstone area and the Taupo Volcanic Zone, New Zealand (Tilling and others, 1973). Thus hydrothermal and segregation quartz veins may have derived their gold from primary volcanogenic deposits. Alternatively, the element may simply have been 'sweated out' of a large volume of 'ordinary' country rock, producing an effective concentration of gold in the veins about 1 000 times that in the source rocks.

The average gold concentrations in the auriferous quartz veins of the Pilbara have not been documented, but since the grade of the ore processed has been about 30 ppm and such ore represents only the richest deposits, a level of 1 or 2 ppm is probably a reasonable estimate. If the average grade of the veins was much greater than this (say 6 ppm) large scale open-cut operations would be profitable. Consequently, the ore-forming process has probably produced concentration levels of about 100 times background.

Most mines based on auriferous quartz veins extend only to a depth of 50 m, and many are far shallower. This feature does not reflect increases in mining costs at depth so much as a general decline in grade. The majority of the economic deposits are supergene enrichments produced by weathering processes.

Detailed descriptions of many of the gold deposits of the Pilbara Block are given by Maitland (1908), Woodward (1911), Finucane (1935-1939) and Finucane and other workers between 1935 and 1939, but no synthesis of gold mineralization has been attempted. The following brief descriptions summarize the main features of each gold mining centre. The deposits are grouped according to their geological relationships (the six principal types listed above).

QUARTZ VEINS IN ARCHAEAN VOLCANIC AND ULTRAMAFIC ROCKS

BAMBOO CREEK

This mining centre is situated 60 km east-northeast of Marble Bar and, having produced about 2 296 kg of gold, is the third most important centre in the Block (Table 7). It is also of interest because it is one of the few mining centres still in operation.

The auriferous quartz veins at Bamboo Creek intrude talc-carbonate and talc-chlorite schists (Chapter 2) which form a 1 km-wide, northwesterly-trending belt of country at the eastern end of the Bamboo Creek-Pear Creek ultramafic zone (Chapter 2). Apart from free gold the veins contain pyrite, arsenopyrite, galena, chalcopyrite, minor tetrahedrite and carbonate gangue. Wolframite occurs at the True Blue mine.

Most of the economic gold deposits of the centre occur in metamorphic dolomite (carbonatized ultramafic rock). Many of the high-grade reefs are composed of numerous quartz stringers rather than thick veins of massive quartz. De la Hunty (1958b, p. 133) noted an association of galena with payable ore and it appears that precipitation of lead and gold occurred preferentially where the veins penetrated zones of carbonate; pyrite, on the other hand, is not a reliable indicator of gold mineralization.

TABLE 7. TOTAL PRODUCTION OF GOLD TO 31 DECEMBER 1977

Mining Centre	*Alluvial (kg)*	*Dollied (kg)*	*Ore (t)*	*Gold (kg)*	*Total Gold (kg)*
Bamboo Creek	0.7	28.1	84 442	2 270.5	2 299.3
Boodalyerrie	—	9.3	122	18.3	27.6
Croydon	—	—	8	0.2	0.2
Eastern Creek	0.44	0.6	7 189	357.1	358.1
Elsie	—	0.3	655	58.0	58.3
Glenroebourne	0.5	0.1	4 413	69.7	70.3
Hong Kong	0.7	—	345	13.9	14.6
Lalla Rookh	—	0.2	11 946	391.9	392.1
Lower Nickol	0.3	0.1	885	13.8	14.2
Mallina	—	—	144	4.0	4.0
Marble Bar	8.7	14.8	208 457	5 443.1	5 466.6
McPhee Creek	—	—	251	10.4	10.4
Middle Creek	0.1	0.6	145 897	2 459.6	2 460.3
Moolyella	—	—	252	0.8	0.8
Mosquito Creek	0.4	6.6	12 373	517.8	524.8
Nickol	—	—	30	0.4	0.4
North Pole	—	—	7 481	118.5	118.5
North Shaw	4.3	18.0	1 868	37.7	60.0
Nullagine	10.1	76.5	16 712	759.5	846.1
Pilbara	0.3	4.2	437	21.4	25.9
Pilgangoora	5.5	1.5	3 191	30.9	37.9
Shark	5.1	1.5	4 046	131.9	138.5
Spinaway Well	—	—	—	0.5	0.5
Station Peak	5.6	1.3	1 128	356.6	363.5
Talga Talga	2.4	5.6	3 874	101.7	109.7
Tambourah	2.8	11.5	5 445	148.9	163.2
Toweranna	—	0.1	4 052	161.7	161.8
Twenty Mile Sandy	1.0	1.5	15 312	475.8	478.3
Upper Nickol	—	—	7	0.1	0.1
Warrawoona	2.2	20.1	25 191	744.5	766.8
Weerianna	—	—	3 592	104.2	104.2
Western Shaw	0.7	2.1	1 315	32.3	35.1
Wodgina	—	1.4	1	—	1.4
Wyman Well	0.1	2.9	6 879	86.5	89.5
Yandicoogina	0.1	12.1	3 903	215.1	227.3
Yule River	8.1	—	—	—	8.1
Sundry Parcels	960.7	24.8	1 374	1 177.5	2 163.0
Total	1 020.8	245.8	593 371	16 334.8	17 601.4

Approximately two-thirds of the production from the centre has come from three mines, the Kitchener, the Mount Prophecy and the Bulletin. The Kitchener mine is positioned on a 150 m long reef which strikes at 305 to 315° and dips steeply northeast; it is offset by two faults lined with barren quartz which Finucane (1936g) used to subdivide the reef into three shoots, northern, intermediate and southern; the southern shoot has been most productive and is mined to a depth of 80 m. The geology of the Mount Prophecy and Bulletin mines is similar to that of the Kitchener, although the reefs at the Bulletin strike almost due east.

De la Hunty (1958b, p. 131) presented results of diamond drilling by the Government of Western Australia conducted on a pound for pound basis with the lease holders. An intersection of 50 g/t over 1 m made at a true depth of 200 m in the Kitchener mine is of special interest; the depth of this ore body is unknown, but its high grade is clearly not a product of near-surface enrichment. Sofoulis (1960b, p. 103) reported intersections of 85 g/t over 2 m at depth of about 150 m and 345 g/t over 2 m at 200 m depth. Allowing for the angle of intersection, a stopable width of 1.1 m would contain an average grade of about 300 g/t (10 oz per ton)—an extremely rich deposit if it were laterally persistent. Although subsequent company drilling indicated that the mineralization is erratic, present (1977) indications are that large scale mining would again be possible at the centre if the price of gold were to rise significantly. In 1975, Meekatharra Minerals N.L. announced probable reserves of 100 000 tonnes of ore assaying 29.7 g/t gold, and possible reserves of 123 000 t averaging 39.6 g/t at the Mount Prophecy and Perseverance mines (*The Miner* newspaper, 11th August, 1975). The same report estimated probable reserves at the True Blue mine to be 100 000 t of ore averaging 17 g/t.

About 30 km to the south-southeast of Bamboo townsite the Twenty Ounce group of mines exploits auriferous quartz veins in mafic and ultramafic schist (Finucane and Sullivan, 1939a). Production from Twenty Ounce is 33 kg from 466 tonnes of ore, plus 1 kg of dollied, alluvial and specimen gold. At the Expectation mine, short but high-grade veins, strike northwest at the margin of the Mount Edgar Batholith. Mining here produced 30 kg of gold from 199 t of ore, and one section of the deposit yielded 21 kg of gold from only 29 t of ore (a grade slightly in excess of 20 oz per t). This unusual concentration of gold was almost certainly related to granitic intrusion.

ELSIE

The Elsie mining centre is situated 60 km east-northeast of Nullagine. Northerly striking mafic and quartz-carbonate schist units surround auriferous quartz veins intruding the more carbonatized rocks. The main workings occur at Mount Elsie, which lies a short distance north of Elsie Well, on GML 625. The principal reef strikes northwest, dips steeply southwest and has been open cut along a length of 40 m (Maitland, 1908, p. 69; Finucane, 1939b, p. 21). The maximum depth of the workings is about 35 m.

GLENROEBOURNE

Two groups of copper-gold deposits occur at the Glenroebourne mining centre: Carlow Castle, and Fortune-Good Luck.

The Carlow Castle workings are situated immediately south of a prominent ridge of chert about 10 km along the road from Roebourne to Chirratta. The chert is correlated with the Towers Formation (Plate 1B). Gold occurs within steeply inclined limonitic quartz veins which strike north at an oblique angle to the chert and surrounding units of metabasalt.

This difference between the orientation of the veins and the adjacent strata is rather unusual but the veins may be dilation fillings or secondary zones of shear associated with strike faulting. The oxidized supergene mineralogy of the deposits is limonite, cuprite, malachite, and azurite, but chalcocite, covellite, bornite, and chalcopyrite are encountered at a depth of about 20 m (near the water table). The chief wall rock is altered metabasalt, but a sill-like unit of serpentinite occurs close to the chert.

The main lode is 60 m long, averages 1 m in width and has been mined to a depth of about 22 m. Gold grades are generally low (about 5 to 10 g/t according to Finucane, Jones and Telford, 1939) and much of the recorded production has come from copper ore.

The Good Luck and Fortune deposits lie about 2 km to the southeast of Carlow Castle. Mining has been based on wide quartz veins striking east-northeast within metagabbro. Although the deposits are large, and have been worked to a depth of 22 m, grade appears to have been only moderate. About 420 t of copper ore were obtained from the Fortune mine between 1901 and 1919. A further 14 t of cupreous ore was extracted in 1963 and 1964.

HONG KONG AND PILBARA

These mining centres lie in a belt of greenstones situated 100 km south-southwest of Port Hedland and 20 km southwest of Kangan homestead.

Most of the production recorded at the Hong Kong mining centre has come from the Empress mine. Here a narrow quartz vein strikes east-northeast through metamorphosed basalt and high-magnesium basalt.

A line of workings follows the strike of the greenstones between the Hong Kong and Foochow mines. The auriferous quartz veins are narrow and short and occur in a band of carbonatized chlorite schist close to a thin unit of metasediments.

At Pilbara a considerable amount of alluvial gold has been obtained from outwash around an east-northeast trending quartz vein known as the Broken Hill line (Sullivan, 1939a). The reef itself strikes almost east, is 200 m long and up to 2 m in width. Assays on material collected by Sullivan (1939a) reveal low gold values. Most of the alluvial gold collected at Pilbara was not officially credited to the centre. This point is clearly illustrated by the fact that the total weight of the two large nuggets collected at Pilbara (1888) and Friendly Creek (1902) is 9.08 kg, a figure greater than the official total production stated in Table 7. The centre was well known for nuggets of lesser size and Sullivan (1939a, p. 3) suggested that a large percentage of the 190 kg of alluvial gold recorded under "Sundry Parcels" from the West Pilbara Goldfield was actually obtained at Pilbara.

LALLA ROOKH

The Lalla Rookh mining centre is situated 110 km southeast of Port Hedland close to the contact between the Lalla Rookh Syncline and the Carlindi Batholith. According to Finucane (1936b, 1937b), virtually all the gold production recorded at the centre came from one mine, the Lalla Rookh.

The mine is positioned on a quartz vein which dips 75° towards 195° and ranges in width from 0.5 m to 3 m. The main reef and a parallel vein 100 m to the southwest are dilation fillings in the axial regions of megascopic kink folds; the latter deform the metamorphic foliation of carbonatized basaltic schist. Other rock types near the workings include metadolerite, ultramafics and arenaceous sediments. A few hundred metres to the northeast of the main shaft there are small exposures of felsic to intermediate agglomerate. This last feature, and geological mapping to the southwest (Hickman and Lipple, 1975), indicate that the stratigraphic level of the ore body is the basal part of the Salgash Subgroup.

When mining was terminated in 1935 both reefs were considered to still contain large amounts of payable ore (Finucane, 1936b, p. 7).

LOWER NICKOL

Gold was first discovered at Lower Nickol in 1890. The gold occurs in steeply inclined quartz veins which strike east-northeast through metasediments and felsic volcanic rocks. The principal quartz vein (Tozer's Reef) is 1 200 m long and dips at 80° towards the south. Mining has been concentrated at the eastern end of the deposit (Finucane, Jones and Telford, 1939).

MARBLE BAR

Marble Bar is the most productive gold mining centre in the Pilbara Block (Table 7). Most of the mines are situated within a 4 km long north-trending belt of carbonatized mafic schist, the southern part of which is positioned very close to the State Battery. On its western side the belt of mafic schist stratigraphically underlies felsic volcanic rocks of the Duffer Formation whereas to the east it is intruded by Archaean alkali-feldspar granite. The auriferous quartz reefs strike north in the central and northern areas, and northwest in the southern section; with a few exceptions they dip west at angles of 10 to 20°. Above the water table the reefs are oxidized and contain considerable amounts of malachite; in the sulphide zone they contain pyrite, chalcopyrite and minor galena. In the Ironclad, Jo-Jo, Viking and Outward Bound East mines the reefs are underlain by granite at depths of only a few metres (Finucane, 1936f, p. 4). These mines are widely spaced along the length of the mineralized zone, which suggests that all the ore bodies are underlain by granite. In detail, the ore bodies consist of thin quartz veins above, below and within sill-like masses of feldspar-chlorite rock (probably metadolerite); gold is confined to the quartz. The main workings extend to depths of between 15 and 30 m, the Stray Shot and the Viking mines being the deepest. The ground occupied by the Stray Shot has yielded over 270 kg of gold with an average ore grade of 58 g/t.

Finucane (1936f) concluded that the Marble Bar field has been largely worked out above the water table and holds little promise of further large scale production. The close proximity of the reefs to the granite suggests that the deposits are probably related to granitic intrusion. The fact that they are essentially stratabound and confined to the belt of mafic schist indicates that either the gold has been 'sweated' from the schist or has been preferentially precipitated within it.

Not all mines grouped into the Marble Bar centre are located at Marble Bar. A major producer outside this mineralized zone is the Comet mine which is situated about 10 km to the southwest of the town (on the road to Wittenoom). Other significant mines include the Blue Bar, 25 km south of the town, and mines of the Corboy and Coongan Belt groups, 40 km south of the Blue Bar.

The Comet mine (Finucane, 1938g) merits brief description because it has yielded over 400 kg of gold from about 22 000 t of ore. Gold mineralization at the Comet mine occurs in a 2 m-wide zone of chlorite-fuchsite-carbonate rock impregnated with fine pyrite and traversed by small veins of quartz and carbonate minerals. The outcrop of the deposits is difficult to distinguish from the surrounding talc-chlorite-carbonate schists of the area and consists essentially of talc-chlorite schist containing hematite and quartz. Finucane (1937a, p. 3) described the outcrop as striking at 225° over 40 m. The ore horizon dips southwards at about 70° and has been mined to a depth of 110 m below the open cut. The main ore shoot plunges (pitches) east-southeast at 40°, the plunge being controlled by the intersection of a main series of fractures, striking west-southwest and dipping south-southeast at 70°, and the regional schistosity of the host rocks which strikes east and dips steeply south. Wall rocks are extensively carbonatized.

Mr J. L. Baxter of the Geological Survey, who visited the mine in 1973, reported metasediments within the ore body and suggested the possiblity that an anticlinal fold closure might be present in the vicinity of the open cut.

NORTH POLE

About 80 per cent of gold produced at the North Pole mining centre has come from the Normay mine which is situated 4 km east of Breens copper mine. Most of the production was recorded between 1949 and 1957, but the mine was still being worked during a visit by the writer in 1972.

Gold mineralization at the Normay mine occurs in a 1.3 m-wide quartz vein which strikes east and is inclined very steeply (> 75°) towards the north. The vein intrudes mafic schist of the Talga Talga Subgroup close to the eastern contact of the intrusive North Pole Adamellite. It crops out over a distance of about 1 000 m and has been open cut to a depth of 10 m over 400 m. The average grade of the deposit is lower than that in most other gold mines in the Pilbara Block but this has apparently been offset by the simplicity of the mining method. Mineralization is almost certainly related to granitic intrusion.

Other mines at the North Pole centre are situated to the northwest of the North Pole Adamellite. Of this group one of the largest past producers is the Democrat which is positioned on quartz veins intruding felsic porphyry (Finucane, 1936a). The veins are irregular and partly of stockwork type but generally dip southeast at about 45°.

Mines to the north and northeast of the Democrat exploit quartz reefs through felsic rocks, altered mafic volcanics and chert. Copper is an important accessory in these deposits, and at Breens is sufficiently concentrated to have been mined (Marston, 1979). Veins of barite intrude the succession to the south of the Democrat. The stratigraphic position of the Breens-Democrat rocks is interpreted as equivalent to that of the Duffer Formation, a facies change accounting for the relatively minor development of felsic and intermediate volcanics.

NORTH SHAW

This mining centre is situated 45 km west-southwest of Marble Bar in schistose amphibolite close to the northern contact of the Shaw Batholith. The North Shaw Tonalite intrudes the metamorphosed mafic volcanic rocks to the east and southeast of the mineralized area. Gold occurs in quartz veins which strike north at the Big Bertha mine, but elsewhere are oriented almost east-west (Jones, 1939a). About half of the recorded gold production from the centre is attributed to sundry claims and none of the mines is large. Mineralization is patchy and rather low grade, and the workings are scattered and shallow.

About 20 km to the southwest of North Shaw a group of mines commonly referred to as the Dalton mining centre accounts for about 10% of the North Shaw total. The principal mine, McLeods Reward, is based on a north-northwest striking line of quartz and quartz-carbonate veins which have intruded the foliation of mafic schist (carbonatized metabasalt). Two shafts have been sunk to depths of about 22 m and sections of the deposits have been open cut. Grades of specimens collected by Finucane (1938b) are generally too low to justify mining.

PILGANGOORA

The bulk of the gold obtained from the Pilgangoora centre has come from mines to the west of McPhee Hill, but minor amounts have also been won from mines to the east of Coffin Bore. All the mines exploit thin north-striking quartz veins (Finucane, 1935a) in carbonatized ultramafic and mafic schist. Recent production from the Birthday Gift has been based on auriferous quartz in mesoscopic saddle reef structures which plunge southwards at 10°.

SHARK

At the Shark mining centre, folded auriferous quartz veins occur in quartz-carbonate-chlorite schist of the McPhee Formation. The most important mine is the Mount Ada, the workings of which follow the crest and eastern limb of a north plunging anticline (Finucane, 1939a). The principal ore-shoots occur in the cores of parasitic minor folds on the main structure. Grades of about 100 g/t over 0.5 m were recorded at the base of the 'North Shoot' in 1936 but production ceased in 1942. The main reef has been open cut and stoped to a depth of about 50 m below the crest of the hill. Gold mineralization is somewhat erratic and several large nuggets have been obtained from alluvial material about 1 km to the west of the lode deposits.

TALGA TALGA

The most important deposits at the Talga Talga mining centre are narrow stratabound quartz veins near the top of the McPhee Formation (quartz-carbonate-chlorite schist), although gold has also been obtained from veins in the underlying North Star Basalt (e.g. North Star mine). Total production appears to be considerably understated in the official statistics (Table 7), because the centre is known to have yielded a large amount of alluvial material. Maitland (1908, p. 40) stated that in 1896 the centre had produced about 62 kg of gold in the form of nuggets.

Most production has been recorded from the McPhee Reward mine (O'Halloran, 1936) which is positioned on quartz veins 0.3 to 0.9 m wide inclined northwest at 30 to 50° and cropping out over a strike length of about 400 m (Finucane, 1936d). The quartz bodies are lenticular and commonly split into parallel stringers. Mineralization is similar to that at Shark except that the Talga Talga veins are not folded. The main ore deposits of these two centres occur at the same stratigraphic level and both are noted for their high content of nuggets.

TAMBOURAH

The Tambourah centre is situated 85 km southwest of Marble Bar, close to the road linking the latter with Wittenoom (via Woodstock). Auriferous quartz veins, generally 0.3 to 0.6 m in width, strike north, parallel to surrounding schistose amphibolite and thin units of metasedimentary rock. A narrow zone of sheared migmatite separates the greenstones from the Tambourah Granodiorite, about 500 m to the west. Numerous workings are scattered throughout the centre, but the richest deposits were located in a reef which extends some 1000 m south from Tambourah Creek parallel to, and about 300 m to the east of, a tributary stream which follows the granite-greenstone contact (Finucane, 1938d, Plate 2).

UPPER NICKOL

The Upper Nickol workings (also referred to as 'Radleys') consist of shallow pits in auriferous quartz veins which intrude sheared mafic-felsic volcanic rocks. The principal mine is approximately 20 m deep and is an open cut (probably stoped) on a 0.5 to 1 m quartz vein through amphibolite schist. The size of the workings indicates that production exceeded the recorded figures (Table 7).

WARRAWOONA

About 20 km southeast of Marble Bar auriferous quartz reefs strike west-northwest within mafic, ultramafic and sedimentary schists on the northeastern limb of the Warrawoona Syncline. The deposits occur in a zone about 7 km long, but less than 2 km wide. Most production has come from a 100 m wide zone of quartz-chlorite schist which extends 4 km along strike immediately to the west and southwest of Warrawoona Peak. The principal mines in this mineralized belt are the Klondyke Boulder (which produced 162 kg), Klondyke Queen (167 kg), Gauntlet (104 kg) and Bow Bells (61 kg). With an average gold content of 44 g/t the ore from these mines was some of the richest material obtained from the Pilbara Block.

Most ore bodies occur close to the contact of quartz-chlorite schist (possibly metamorphosed sediments or pyroclastics) and carbonate-chlorite schist. According to Jones (1938, p. 4) gold is concentrated where north-northwest striking faults cross such contacts to form pipes of quartz which plunge northwards at 65°. The workings extend to a depth of 60 m, and Jones stated that grades do not greatly diminish at depth; in fact in the Klondyke Boulder at the 60 m level 400 t of ore yielded 33 kg of gold, and the ore body is wider than in higher sections of the mine.

WEERIANNA

The Weerianna mining centre is situated 300 m to the south of the North West Coastal Highway, 3.5 km west of Roebourne. Gold occurs in chert and quartz veins which strike east-northeast to north along the northwestern side of a chert ridge. The principal host rock is mafic schist forming part of the Towers Formation and the lower part of the Apex Basalt. Apart from gold, the reefs contain pyrite, chalcopyrite and galena. None of these metals occur in economic concentrations at Weerianna but about 1.4 km to the south, 1 030.25 t of copper ore has been mined from the Lilly Blanche mine (Marston, 1979).

The bulk of the gold won from the centre has come from the Hillside and Perseverance mines. Three folded quartz veins at the Hillside mine have been mined to a depth of 28 m. The most productive reef is over 30 m in length and ranges up to 1.5 m wide. At the Perseverance mine (also known as Shaws), 500 m west-southwest of the Hillside, three parallel quartz-chert deposits up to 3 m in width dip steeply toward the north-northwest (Finucane, Jones and Telford, 1939).

Granitic cupolas intrude amphibolite (metagabbro and metabasalt) a short distance to the southwest of Roebourne, and may underlie the Weerianna centre at fairly shallow depth. Hydrothermal quartz veins associated with granitic intrusion appear to have selectively intruded the chert horizons, precipitating gold in the process.

WESTERN SHAW

The geology of the Western Shaw mining centre (Finucane, 1938d) is similar to that at Tambourah which lies immediately to the north. Gold mineralization occurs in lenticular quartz veins which strike north within a sequence of mafic schist and arenaceous metasediments. As at Tambourah, the veins are parallel to adjacent strata and dip east at 70 to 80°.

WYMAN WELL

The Wyman Well mining centre which includes mines between the Salgash-Apex area (Finucane, 1938f, 1939c) and the Copenhagen mine, is located about 15 km south of Marble Bar. At Copenhagen several shafts have been sunk on copper-gold mineralization within quartz veins. These veins intrude the principal foliation (bedding and schistosity are broadly parallel) of carbonatized ultramafic rock and siliceous cataclasite which occupy a 12 m wide belt between two chert units. Water has flooded the workings to the 8 m level. Malachite and azurite are conspicuous supergene minerals on surrounding dumps.

The Euro mine has produced about 23 kg of gold from 653 t of ore, and the Pheonix 14 kg from 90 t of ore, plus 10 kg dollied. Details of workings of the Euro are not available, but the Pheonix is based on a quartz vein striking northwest through mafic schist. The deposit has been stoped to a depth of 30 m (Finucane, 1939c, p. 3).

YANDICOOGINA

The Yandicoogina deposits (Finucane, 1939e) form an extension of the mineralized zone at Warrawoona but their geological setting is different. Auriferous quartz veins occur within a zone of intense shear along the southeastern margin of the Mount Edgar Batholith. The veins intrude sedimentary and felsic schist of the Warrawoona Group and sheared granitic rocks. The largest mine is the Uncle Tom which has produced 55 kg of gold from 974 t of ore.

The main reef at the Uncle Tom mine strikes east-northeast, dips to the south at about 45° and can be traced laterally for 250 m. It has been stoped to an average depth of 16 m over 43 m. The lode is about 1 m thick and is flanked by granite. To the north of the shear zone the foliated granitic rocks of the Mount Edgar Batholith have been intruded by a non-foliated mass which is probably a small post-tectonic pluton. It is uncertain whether the auriferous quartz veins at Yandicoogina are segregations associated with deformation or if they are hydrothermal deposits.

QUARTZ VEINS IN ARCHAEAN SEDIMENTARY ROCKS

Of the various Archaean sedimentary units in the Pilbara Block only the Mosquito Creek Formation contains signficant deposits of gold and these are located mainly in pelitic members. As in volcanic rocks the deposits take the form of auriferous quartz veins generally parallel to the strike. Most of the important mines are remote from exposed granitic intrusions but at Station Peak mineralization follows the contact of a mafic sill.

The association of gold mineralization with pelitic rocks suggests that the gold is derived either from these sediments or that it is preferentially precipitated within them. At Mosquito Creek the Mosquito Creek Formation unconformably overlies the Warrawoona Group. It is possible that gold weathered from the volcanics was redeposited in a sedimentary environment, and subsequently concentrated during deformation and quartz veining.

EASTERN CREEK

This centre is situated 60 km east-northeast of Nullagine close to the northern margin of the Mosquito Creek Synclinorium. To the north of the centre of the base of the Mosquito Creek Formation consists of conglomerate, sandstone and psammitic schist dipping south at about 45°. This basal sequence is overlain by more pelitic strata which crop out close to the mines.

Finucane (1939b, p. 19) described two lines of reefs striking east-northeast and dipping south at about 50°. Most production has been recorded from Doherty's Reward mine which is situated on the northern line about 0.8 km west of the Eastern Creek Government Well. Pelitic schist containing thin psammitic bands is the principal host rock and the auriferous quartz veins may be related to a fault which follows the course of the track leading to Mosquito Creek. A porphyritic intrusion occurs to the east of the Crescent mine, but it is uncertain if this bears any relationship to the mineralization.

MIDDLE CREEK

The largest producer of gold from quartz veins in sedimentary rock is the Middle Creek mining centre. It is situated 20 km east of Nullagine and includes a group of mines close to Barton Battery and the well known Blue Spec mine 8 km to the north.

The Blue Spec gold-antimony mineralization occurs in a east-striking shear zone through pelitic and psammitic schist of the Mosquito Creek Formation (Finucane, 1936e). A smaller but similar occurrence is located at Golden Spec, 1 km to the west of Blue Spec. Just prior to its closure in January, 1978, the Blue Spec mine had produced 1 863 kg of gold, and concentrates containing 1 490 t of antimony from 110 033 t of ore. Mining occurred in two main phases. From 1935 to 1962 ore was extracted down to the 176 m level, while from 1976 to 1978 mining was extended down to approximately 317 m, at which stage virtually all the identified ore reserves had been extracted.

The shear zone is 15 m to 20 m wide and carries traces of gold beyond the limits of the main lodes. The lodes occur close to the northern and southern margins of the shear zone, dip vertically or steeply south, and contain quartz carrying stibnite, aurostibite and native gold. Pyrite, pyrrhotite, and carbonate are irregularly distributed while minor scheelite, arsenophyrite, marcasite, sphalerite, chalcopyrite, magnetite, mackinawite, calaverite, rickardite, and gudmundite have been recorded. Cervantite was common in the oxidized zone and traces of mercury and lead have been noted in the assays of stibnite concentrates. Because of the high percentage of gold contained in the mineral aurostibite (Au Sb_2), the ore is notoriously difficult to treat and has resulted in the loss of between one third to one half of the gold and antimony into the tailings.

The generalized structure is a drawn out and faulted series of mineralized elements or 'pods' forming a 'Z' fold repetition plunging to the east, the whole being contained in a localized section of the Blue Spec shear zone (Mulga Mines Pty Ltd Information Sheet, 1976). Shearing on the east-west line, which extends from Blue Spec about 5 km to the west and 16 km to the east, appears to have occurred during gold and antimony mineralization because it controls the shape and limits of the ore bodies yet visibly deforms crystals of stibnite (J. L. Baxter, pers. comm.). There are two principal ore zones, a northern zone where the lodes occupy tensional fractures and a zone which follows the southern limit of the shear. The ore zones are irregular in shape and there are few well-defined walls to the southern lode. This feature has resulted in ore dilution during mining. On payable gold values the width of the southern lode varies from 1 m to 4 m (McKeown, 1953, p. 239). The northern lode, which diverges from the southern lode near the main shaft, strikes east-northeast, is vertical and about 0.6 m wide. It carries irregular high-grade stibnite ore.

Although Blue Spec accounts for the bulk of gold production at the Middle Creek centre, most of the mines are situated along an east-northeast trending line between the Barton Battery and the Twenty Mile Sandy Battery. This mineralized zone coincides with a 2 km wide outcrop of dominantly pelitic schist (a unit which Noldart and Wyatt (1962, p. 103) referred to as the Middle Creek Formation, now regarded as a member of the Mosquito Creek Formation).

The most important mine in this group is the Barton which has produced over 200 kg of gold. Here the quartz reefs strike north-northeast to northeast and are inclined southeast at about 60°. Four main shoots of ore plunge ('pitch') northeast at about 40°, a direction which coincides with the intersection of the quartz veins with the cleavage in the surrounding schists. Other mines in the Middle Creek centre are also based on quartz veins through pelitic schist. The orientation of these veins is generally at an angle to cleavage, and Finucane (1939b) stated that they occupy faults. Such faults may belong to the D3 episode of regional east-west compression (Chapter 6).

MOSQUITO CREEK

This mining centre is situated 40 km east of Nullagine and includes two groups of mines. The southern group has exploited auriferous quartz veins in an eastern continuation of the belt of pelitic schist which occurs at Middle Creek and Twenty Mile Sandy. Of these mines the largest producers have been the Galteemore (138 kg from 2 213 t of ore) and the Ard Patrick (102 kg from 1 248 t of ore). Both mines ceased operations in about 1913.

The Galteemore reef strikes east for 150 m, varies in width from 0.3 m to 1.0 m and is vertical. Wall rocks consist chiefly of pelitic schist and quartz carrying minor pyrite. Workings extend below 30 m from the surface but are inaccessible. The Ard Patrick mine is situated about 900 m west of Galteemore and has a similar geological setting. Work has been based on an east-northeast-striking quartz vein which varies in width between 0.2 m and 1 m and dips north at 70°. The quartz is iron stained and carries minor pyrite; scheelite occurs in bunches associated with gold in the western part of the reef (Simpson, 1952, p. 531; Blatchford, 1913, p. 129).

The northern group of mines is situated 2 km east of Granite Hills Well. Here a pelitic schist unit carries northwest and west-striking quartz veins. About 86 kg of gold have been obtained from 3 286 t of ore. The principal mine is the Parnell where a 0.7 m to 1.5 m quartz vein has been worked to a depth of 49 m (Maitland, 1908, p. 77).

NULLAGINE

The Nullagine mining centre is best known for its Proterozoic alluvial deposits, but about half of its gold production has been obtained from the Mosquito Creek Formation. Most of the mines occur in a belt of country between Middle Creek and Cajuput Spring but several others are grouped close to the confluence of Cajuput Creek and the Nullagine River. The largest single producer has been the Mundalla (54 kg) which is located 1 km east of Five Mile Creek a short distance south of the road to Middle Creek. On the opposite bank of Five Mile Creek the Castlemaine has yielded 41 kg of gold, 34 kg of which came from only 6 t of ore. From descriptions by Maitland (1908, p. 136-143) it is clear that most of the workings are based on northeast-striking pyritiferous quartz veins through pelitic schist; that is, they are of a similar type to those at the Middle Creek, Mosquito Creek and Twenty Mile Sandy mining centres.

TWENTY MILE SANDY

The geology of the Twenty Mile Sandy mining centre is virtually identical to that of Middle Creek. A southern group of mines is situated in the belt of pelitic schist, informally referred to as the 'Middle Creek Member', and a northern group lies on the Blue Spec-Billjim shear zone. The Billjim mine has been an important producer, recording 97 kg of gold from 4 596 t of ore. Here a 0.5 to 1.0 m wide quartz vein carrying gold and antimony intrudes the cleavage of pelitic schist and is inclined steeply northwards.

The most productive mine of the southern group has been the Little Wonder, located 4 km west of the Twenty Mile Sandy Battery. The Little Wonder deposits have yielded about 170 kg of gold from 5 131 t of ore. The reef strikes east-southeast, dips steeply to the north and in 1939 had been worked to a depth of 51 m (Finucane, 1939b, p. 10). Subsequent work between 1939 and 1951 resulting in the removal of 3 643 t of ore, must have considerably extended the mine, but no details are available.

MALLINA

Gold was first discovered at Mallina homestead in 1888. Two deposits have been worked, one 100 m north of the homestead and another 500 m east-northeast of the homestead. The homestead deposit is a narrow quartz vein immediately to the south of a 6 m wide quartz vein which strikes east (Woodward, 1911, p. 77-79; Telford, 1939a, p. 9). The eastern reef is 120 m long and generally about 2 to 3 m thick. Both veins are broadly parallel to the strike of surrounding pelitic and psammitic schists and dip steeply northwards. As at Blue Spec and Billjim, the ore contains large amounts of antimony.

STATION PEAK

Station Peak is situated 50 km southeast of Whim Creek and 100 km south-southwest of Port Hedland. Virtually all of the production from the mining centre has come from the Pilgrim's Rest mine which is based on quartz veins close to the southern margin of a major gabbro sill (Woodward, 1911, p. 89; Blatchford, 1913, p. 143; Finucane, 1937c, p. 3-7). The sill intrudes pelitic to psammitic metasediments of the Mosquito Creek Formation. The main auriferous quartz vein strikes almost due east and dips south at about 65°. It varies in width up to 4 m and is composed of bluish quartz with pyrite, arsenopyrite and chalcopyrite. Oxidation extends to a depth of about 30 m and this upper section has yielded the highest grade ore.

Formation of the mineralized quartz veins obviously followed intrusion of the gabbro sill, but it is possible that intrusion of the latter may have led to some initial concentration of gold close to the southern contact. Quartz veins at Station Peak have a range of orientations, some being parallel to the margins of the sill whereas others strike northwest or northeast. The veins fill fractures which probably originated during the main episode of deformation as a result of differing behaviour of the sill and the surrounding sedimentary rocks under stress.

QUARTZ VEINS IN ARCHAEAN GRANITIC ROCKS

Apart from auriferous quartz veins in sheared migmatitic granitic rocks at the Yandicoogina mining centre, Archaean granitic rocks are host to gold mineralization only at the Boodalyerrie mining centre.

BOODALYERRIE

According to Maitland (1908, 1919) and Finucane (1939d) the Boodalyerrie centre (production period 1900-1910) is situated close to the southern contact of the Yilgalong Granite, but the precise position of the workings is unknown. Maitland (1908, p. 73-75) stated that the main deposit "consists of an irregular network of small quartz leaders occurring in close proximity to a greenstone [presumably dolerite] 'dyke'". Mining has been concentrated on a zone of alteration inclined 65° towards the southwest. Statements by Maitland indicate that the actual production from the centre is about twice the official figure.

QUARTZ VEINS IN ARCHAEAN QUARTZ-FELDSPAR PORPHYRY

Gold mineralization of quartz-feldspar porphyry intrusions occurs at the North Pole and Toweranna centres. The Democrat mine at North Pole (referred to previously) has produced relatively little gold (7.14 kg).

TOWERANNA

The Toweranna mining centre is situated 15 km south-southeast of Whim Creek and 100 km southwest of Port Hedland. Auriferous quartz veins, which strike north to north-northeast and are inclined at 30 to 40° towards the east (Telford, 1939b), intrude a small stock of quartz and feldspar-phyric dacite porphyry.

This porphyry crops out over 2 km^2 within the axial region of a northerly plunging anticline (Croydon Anticline). Dykes of similar porphyry occupy the axis of this fold 13 km to the south, suggesting that emplacement of the porphyry, and probably the quartz veins also, is structurally controlled. Pyrite and magnetite occur in the porphyry but its general gold content is unknown. Gold mineralization extends into the surrounding metasediments, but the presence of the porphyry has obviously played an important role in the genesis of the deposits. During its intrusion the prophyry may have accumulated gold from the Mosquito Creek Formation and provided a source for further concentration within quartz veins during subsequent deformation.

PROTEROZOIC CONGLOMERATE DEPOSITS

Gold has been mined for placer deposits in Proterozoic conglomerate units at Nullagine and Marble Bar. The deposits have been compared with the Witwatersrand gold deposits of South Africa, although there are significant sedimentological differences.

NULLAGINE

About 2 km to the northwest of Nullagine the Mosquito Creek Formation is unconformably overlain by the Beatons Creek Conglomerate Member of the Lower Proterozoic Hardey Sandstone. Within the lower 30 m of this conglomerate are several 0.5 to 4 m thick pyritiferous and auriferous units. The pyrite occurs as small crystals and rounded nodules within the matrix of the conglomerate. Gold is generally fine but also forms small flakes and rounded particles in the matrix. Lithic components of the rock reveal derivation of the conglomerate from the Mosquito Creek Formation, and rare granitic boulders probably originate from the Kurrana Batholith.

The auriferous zones are typically discoloured by oxides of iron and mining has been concentrated where hematite, limonite, and jarosite predominate over pyrite. The Hardey Sandstone dips west at 20 to 30° at Grants Hill, but farther west its attitude is reversed across the axis of a southwesterly plunging syncline. This syncline was recognized by Finucane (1935b) who noted a continuation of gold mineralization into the western limb. No mining has been undertaken on the western limb and this area merits further investigation.

Although the auriferous beds at Grants Hill rest directly on Archaean rocks the same horizon farther west is underlain by several hundred metres of Proterozoic sandstone and porphyry. At Nullagine the Hardey Sandstone was deposited on the south-eastern side of a depositional basin, and the placers probably formed in stream channels draining the area to the southeast. The detrital gold is thus assumed to have been derived from the Mosquito Creek Formation between Nullagine and Middle Creek. Maitland (1905, p. 41) reached essentially the same conclusion, but added that "by far the bulk of the gold, together with the pyrite, was introduced by solutions percolating down the most porous portions of the conglomerate". Supergene enrichment is a feature of the deposits but there seems little doubt that the ore bodies are of sedimentary origin. The deposits differ from the Witwatersrand deposits in being composed of poorly sorted boulders (up to 1 metre in diameter) and not being conspicuously cross-bedded. They probably formed in relatively steep channels and show no signs of reworking. It is possible that conglomerate of deltaic, Witwatersrand type may underlie the area between Nullagine and Copper Hills.

MARBLE BAR

Beds of auriferous conglomerate up to 2 m in thickness have been worked at the Just-in-time mine 9 km south-southwest of Marble Bar (Finucane, 1938a). The conglomerate is Lower Proterozoic in age and locally forms a basal member of the Mount Roe Basalt. The ore body is lenticular and occupies a depression in the underlying Archaean chlorite-carbonate schists, indicating that it formed in a stream channel. About 2 kg of gold have been officially recorded from the mine, but the size of the workings suggest substantially more production.

About 3 km northwest of Just-in-time, similar conglomerate has been worked at the Tassy Queen (Finucane, 1938a) where, between 1935 and 1946, 71 kg of gold were obtained from 4 061 t of ore.

Noldart and Wyatt (1962, p. 136) refer to minor gold production from auriferous Proterozoic conglomerate in the Apex-Salgash area, but the exact position of these workings does not appear to have been recorded

CAINOZOIC ALLUVIAL-COLLUVIAL DEPOSITS

Most of the gold mining centres in the Pilbara Block have recorded gold production from Cainozoic alluvium and colluvium. These deposits result from the disintegration of Archaean and Proterozoic ore bodies under normal conditions of surface weathering. Gravel, sand and finer particles are washed downslope over scree slopes and into stream channels. Being far denser than other constituents of this detritus, gold particles have tended to be deposited in the upper reaches of channels as soon as stream velocity becomes insufficient to carry them in suspension. Further concentration occurs because agitation of stream sediments causes the heaviest particles to move downwards towards the base of the channels. Thus, auriferous alluvium and colluvium is generally situated quite close to the primary lode deposits and the richest material is found in the lower layers of sediment in any particular channel.

Table 7 shows that 1266 kg of alluvial and dollied gold have come from centres in the Pilbara Block but of this figure only 281 kg have been recorded from specific localities, the balance being reported by banks and gold dealers as derived from the area generally. One of the more important sources has been Nullagine where creeks draining the auriferous conglomerate of the Hardey Sandstone have probably yielded in excess of 150 kg (Finucane, 1936c).

The bulk of alluvial gold occurs in the form of fine grains but some deposits contain quite sizeable pieces referred to as 'nuggets'. Most nuggets are only 5 to 10 mm across but specimens up to 300 mm in diameter have also been found.

GOLD NUGGETS

Eight gold nuggets, each weighing more than 3.9 kg (125 oz) have been recorded from the Pilbara Block. In 1888 Mr. A. Villars found a 3.95 kg nugget near Pilbara Well (the exact location of the find is not recorded). Two years later Mr. J. Doyle discovered a large nugget at a locality variously referred to as Shaw Falls or Pantomime Gully, 3 km south of Shark (Simpson, 1902, p 12). The nugget, which was subsequently named the 'Little Hero' weighed 10.36 kg, and the metallic portion contained 87% gold and 13% silver. It was sold for £1 257. Apart from gold it contained ferruginous quartz and travertine.

In 1896 Mr. Anderson picked up a 4.98 kg gold nugget at Croydon, but the largest nuggets ever discovered in the Pilbara Block were found three years later, again at Shark. The 'Bobby Dazzler' collected by Mr. A. Clive, was similar in composition to the Little Hero, the ore fraction assaying 76.81% gold, 23.04% silver and 0.15% copper and iron; Simpson (1902) stated that the nugget contained 50% by volume and 16% by weight of ferruginous quartz. It measured approximately 250 mm x 200 mm x 80 mm and tipped the scales at 15.15 kg. For about 30 years it was the largest true alluvial nugget obtained from the Western Australian goldfields, but in 1931 the 'Golden Eagle', a quite exceptional specimen weighing 35.30 kg was found at Larkinville 80 km south of Kalgoorlie.

In the same year, and at the locality where the Bobby Dazzler was discovered, two brothers, W. and H. McPhee, picked up the 'General Gordon'. Of similar composition to Mr Clive's nugget this specimen was only slightly smaller, weighing 11.57 kg. Finucane (1939a) indicated that the exact locality of the 1899 discoveries is situated 1.2 km southwest of the Mount Ada mine, on a creek running west from the Shark line of reefs. Models of the Bobby Dazzler, the General Gordon and the Golden Eagle are on display in the museum of the Geological Survey of Western Australia.

Another large nugget was found at Friendly Creek by Mr. S. Willcocks in 1902. It weighed 5.13 kg and contained 93.45% gold and 6.00% silver. On 17 July, 1903 the 'Kalgoorlie Miner' newspaper reported that Mr. A. Clive had found another nugget at the Bobby Dazzler locality. It was stated to weigh 6.50 kg and to have been obtained from alluvium at a depth less than 1 m; this find was also noted by Crockett (1904, p 31), who recorded the discovery of a 5.44 kg nugget at the Talga Talga centre. This nugget was found by Mr. J. Cain in 1903 and contained 4.04 kg of pure gold. It is notable that primary gold mineralization at Shark, Talga Talga, and probably Friendly Creek also, occurs in the McPhee Formation; other centres not based on this formation have produced far more gold but have not yielded large nuggets.

STRATIGRAPHIC CONTROL OF GOLD MINERALIZATION

If (as other workers have suggested) gold mineralization in the Pilbara is intimately related to granitic intrusions, the ore bodies should be distributed more or less randomly through the succession of the Pilbara Supergroup because virtually all parts of that succession are intruded. Plate 1B indicates, however, that certain

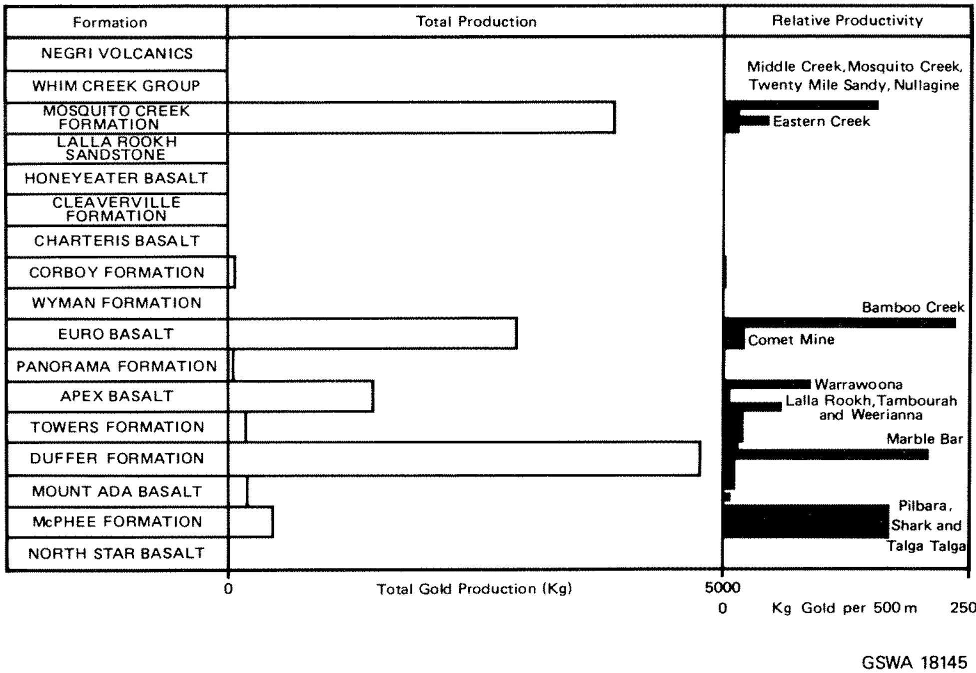


Figure 49. Total gold production and relative concentration levels in the Pilbara Supergroup.

stratigraphic levels or horizons contain most of the deposits. This relationship is illustrated in Figure 49 which plots recorded production against stratigraphic level. Four of the seventeen main stratigraphic units have accounted for over 90% of the total production.

The Bamboo Creek and Marble Bar centres occur at levels not containing significant gold mineralization elsewhere and appear to owe their existence to local geological factors: on the other hand, the Apex Basalt and the Mosquito Creek Formation contain gold deposits in many parts of the Pilbara Block, and the McPhee Formation is mineralized in most areas where it crops out.

Proterozoic gold deposits are placer concentrations in conglomerate units of the Fortescue Group. Conglomerate at the base of the Mount Roe Basalt is auriferous at Just-in-time, Salgash and Miralga Creek (anomalous gold contents noted by Hickman, 1977a), and in the Hardey Sandstone at Nullagine. All these conglomerates immediately overlie Archaean rocks and are situated within a few kilometres of Archaean auriferous source regions.

METALLIC MINERALS

ANTIMONY

Antimony was first mined in the Pilbara Block at Mallina in 1903. From that date to about 1940 production figures are incomplete, and the data for the Mallina, Peawah, and Sherlock centres in Table 8 must be regarded as approximate. With the possible exception of Balla Balla, all the antimony has been obtained from quartz-stibnite (± cervantite) veins in pelitic units of the Mosquito Creek Formation. Antimony concentration levels in shales and slates are generally about 10 times greater than in igneous rocks (Onishi, 1970). This is attributed to concentration in low-energy, reducing, depositional environments. Pyrite, arsenophyrite, and carbonaceous materials are common in such shales, and they are generally dark grey to black (Mason, 1966, p. 182).

The Pilbara antimony deposits occur chiefly along shear-zones veined by quartz. Antimony in the shales (original antimony content probably 1-10 ppm) appears to have been 'sweated out' and concentrated in the veins; Finucane and Telford (1939b, p. 5) quote average grades of between 1 and 6%.

TABLE 8. PRODUCTION OF ANTIMONY TO 31 DECEMBER 1977

Centre	*Concentrate* (t)	*Contained antimony* (t)
Balla Balla	22.64	12.36
Blue Spec	3095.00	1489.65
Billjim Group	61.95	31.95
Mallina (a)	47.60	(b) 2.57
Peawah (a)	21.08	11.77
Sherlock (a)	22.00	11.03
TOTAL	3270.27	1559.33

(a) Data from Finucane and Telford (1939b, p. 6)
(b) From 7.21 t of concentrate, records incomplete

The Blue Spec, Billjim, and Mallina mines are described in the section on gold. The Balla Balla production came chiefly from the Star mine, 10 km northeast of Mount Negri (Finucane and Telford, 1939b, p. 5), where a 60 m long, 0.5 m wide quartz vein containing stibnite and oxides of antimony intrudes the Louden Volcanics (mine geology is uncertain because the workings were not found). The Peawah mine is 10 km east of Mallina, and the geological setting is similar. The Sherlock workings are on the east bank of the Sherlock River about 10 km south of the North West Coastal Highway.

BERYLLIUM

About 2 600 t of beryl ore containing 300 tonnes of BeO have been mined from the Pilbara Block (Table 9); this is approximately two-thirds of Western Australia's total production. Beryl is chiefly found in rare-metal pegmatites (Chapter 2) and associated alluvial and eluvial deposits. It is understandable therefore that the main centres of production include most of those mined for tantalite.

WODGINA

The principal source of beryl in the Pilbara has been the 'Tantalite Lode' at Wodgina (Chapter 2). Production was chiefly from one concentration within the lode, and the remainder of the deposit is not sufficiently enriched in the mineral to warrant mining (Ellis, 1950, p. 55). Other deposits at Wodgina have contributed to the centre's total production of 927.71 t of concentrate.

MOUNT FRANCISCO

Beryl has been mined from numerous claims at Mount Francisco, most of which are situated about 1 km south of the 'Mount' (trigonometrical station B10), although workings have also been noted northwest of this reference point. Almost 7 t of the Mount Francisco total came from Numbana and yielded 0.92 t BeO. Another 20 t of beryl concentrate (containing 2.4 t BeO) was obtained from Mundermullancunder Pool, 16 km east-southeast of Mount Francisco, probably from pegmatite similar to that at Numbana.

TABLE 9. TOTAL PRODUCTION OF BERYLLIUM (as BeO) TO 31 DECEMBER 1977

Centre	*Ore (t)*	*Contained BeO (kg)*
Abydos Station	17.81	2 073.8
Ailsa Downs	61.68	7 427.1
Cooglegong	96.18	11 375.2
Eley	0.60	73.4
Hillside Station	10.23	1 288.4
Lalla Rookh Station	73.09	8 582.5
Moolyella	12.20	1 277.0
Mount Francisco	268.94	31 667.4
Mount Welcome	0.28	34.7
Nimingarra Station	26.38	2 875.6
Pilgangoora	2.11	266.8
Pippingarra	205.00	24 629.5
Roebourne	106.42	11 837.1
Strelley	38.56	4 346.4
Tabba Tabba	52.36	5 859.6
Twenty Mile Creek	0.60	60.9
Upper Five Mile Creek	9.57	1 092.3
Wallareenya	0.84	98.7
Whim Creek	3.44	401.6
Wodgina	927.71	106 902.3
District Generally	687.85	77 875.9
TOTAL	2 601.85	300 046.2

PIPPINGARRA

Virtually all the beryl recorded from the Pippingarra mine was obtained within MC 313 which covers a coarse-textured microcline pegmatite (Chapter 2). Minor quantities of cassiterite and tantalite are also present in the lode.

COOGLEGONG

The origin of the beryl production recorded at Coolegong is unknown, although the mineral has been noted at two localities within the Cooglegong Adamellite. It also occurs 5 km southwest of Calvert's White Quartz Hill in pegmatite cutting mafic rock of the Salgash Subgroup.

STRELLEY

About half of the production from the Strelley centre was obtained from MC 106 at Strelley mine. Ellis (1950, p. 71) commented that occasional idiomorphic crystals of beryl up to 100 mm long were present in 1944. Some masses weighed up to 40 kg, and Ellis was able to collect 5 t of beryl from adjacent superficial deposits. Most of the remaining Strelley production came from workings near Turkey Camp Well, 27 km south-southeast of Strelley mine. In 1975, these workings, which consist of shallow pits in microcline-quartz-mica pegmatite, still contained beryl crystals up to 50 mm long; tantalite minerals are also present at this locality. The pegmatite veins intrude foliated adamellite close to the margin of a large intrusion of poorly foliated potassic granite, which is considered to be of post-tectonic origin (Plate 1A).

LALLA ROOKH

Virtually all the beryl production from Lalla Rookh came from MC 304 in the Turkey Camp Well area. As the claim was never surveyed its precise location is uncertain. Mines plans record its position as 3 km southeast of the well, but the writer has not observed workings in that area. It is possible that MC 304 is close to MC 354, the area described above as part of the Strelley centre. Alternatively, workings about 0.5 km east of the well may be the source of the beryl.

TABBA TABBA

About 47 t of beryl concentrate was mined from MC 116, which was located close to central part of the main tantalite lode at Tabba Tabba. Ellis (1950, p. 55) recorded beryl crystals up to 250 mm wide and 150 mm long in the southern part of the pegmatite vein. It is not known what proportion of the production came from primary and secondary deposits, but some may have been mined from an " . . . . unusual beryl pegmatite . . . . " described by Ellis (1950). Beryl constituted up to 25% of this rock, in which it occurred as small white crystals up to 40 mm wide within a matrix of quartz and albite.

ROEBOURNE

In 1960, a group of Aboriginals led by Mr. D. McLeod obtained about 106 t of beryl concentrate from pegmatite and alluvium 2 km south of Mount Hall. According to Ellis (1962), the beryl occurs both as massive crystals up to several tonnes in weight and as disseminations. The largest individual crystals are said to measure "several inches" across, but the pegmatites are far smaller than those at Wodgina, Pilgangoora, Strelley, and Tabba Tabba.

AILSA DOWNS

Over 60 t of beryl concentrate are recorded from "Ailsa Downs Station," but unfortunately there is no evidence that such a property ever existed. Information given at the time production was recorded places the position of the deposit as 40 km south of Wodgina. It may be situated close to Ailsa Well.

OTHER AREAS

Production of beryl from areas other than those referred to above has been relatively minor. The Nimingarra deposit has not been found, and the Upper Five Mile mine is referred to during the discussion of tantalite production.

CHROMIUM

No chromium production has been recorded from the Pilbara Block, but chromite deposits are known to exist at two localities, Pear Creek and Nobb Well.

At Pear Creek, 19 km west of Eginbah, chromite occurs as disseminated grains in a serpentinized peridotite. Lenses of peridotite containing over 50% of the mineral form local enrichments up to 1 or 2 metres across, but in general chromite constitutes less than 5% of the rock. A cherty cap rock on a ridge northwest of the main occurrence assayed 2.0% chromium, and gossanous material from the same rock yielded 3.0% chromium (as did another gossan 1 km to the east). Chromium concentrations are anomalously high in the peridotite, but too low to constitute ore-grade material. About 10 km to the east-southeast, the serpentinized peridotite contains gossans with up to 0.53% chromium and 0.68% nickel. The ultramafic forms part of the 70 km long intrusion extending from Pear Creek to Bamboo Creek. On the eastern side of the Talga River, two samples of gossanous material from green chert near the contact of the peridotite assayed 0.64% and 0.85% chromium.

The Nobb Well occurrence is situated 7 km southwest of Bamboo Creek Mining Centre. Here a serpentinized peridotite, not physically connected, but possibly genetically related to that mentioned above, contains disseminated chromite. One sample of the rock assayed 3.15% chromium and a silicic cap rock returned 0.22% chromium. No other samples of the rock were collected, and the ultramafic probably merits further investigation; its position is shown by Hickman and Chin (1977, map).

COPPER

Copper deposits of the Pilbara Block have been described by Low (1963) and Marston (1979). Production commenced at Roebourne in 1872 (Simpson and Gibson, 1907), and in 1873, records show that 60 t were exported from Cossack; total production of the metal from copper ore and cupreous ore (in the area covered by Plate 1A) to the end of 1977 amounts to 17 069 t, about 94% of which has come from three centres, Whim Creek, Yannery Hill and Copper Hills. Total ore extracted in yielding this copper has been 124 769 t so that average grade for all mines is 13.7% Cu. As Low (1963, p. 28) pointed out, this figure exaggerates the true grade of the deposits because much of the early ore production (including that from Whim Creek) represents concentrates. Production from individual centres is listed in Table 10.

Marston (1979) classified the copper deposits of Western Australia according to their geological setting and the nature of the ore; readers requiring a detailed description of copper mineralization in the Pilbara Block are referred to his work. The most important types of deposit, in terms of past production, regional distribution and economic potential, occur in felsic volcanic and sedimentary rocks. The various geological environments of the deposits which account for the production figures listed in Table 10 are briefly described in order of proven economic importance.

TABLE 10. TOTAL PRODUCTION OF COPPER TO 31 DECEMBER 1977

Centre	*Copper ore and concentrates (t)*	*Cupreous ore and concentrates (t)*	*Contained copper (t)*
Abydos		10.43	0.91
Boodalyerrie		0.95	0.62
Boodarrie		1.22	0.07
Copper Gorge		2.13	0.75
Copper Hills	472.17	15 614.39	2 107.24
Croydon	613.69	104.24	118.37
Doherty		9.43	1.23
Egina	550.99	29.05	109.12
Glenroebourne	2 601.19	40.02	459.41
Kelly	0.54	609.69	119.01
Lalla Rookh		13.81	2.07
Lennon Find	5.89	28.92	4.93
Lionel	39.71	372.10	67.77
Marble Bar	11.20	125.39	17.36
Middle Creek	7.62	4.04	0.77
Mount Berghaus		1.20	0.11
Mount Francisco		4.24	0.18
North Pole	53.02	289.60	41.49
North Shaw	7.89	5.06	2.73
Pilgangoora		23.36	1.74
Whim Creek	79 263.80	12 322.24	11 511.37
Wodgina		3.71	0.23
Woodstock		9.09	0.74
Wyman Well		2.09	0.29
Yannery Hill	8 490.80	3 005.79	2 500.71
TOTAL	92 118.51	32 632.19	17 069.22

WHIM CREEK

The Whim Creek mining centre includes the mines of Whim Creek (Whim Well), Mons Cupri and three smaller workings, Mons Cupri Northwest, Rushalls, and Western Hill (Finucane and Sullivan, 1939b). Only Whim Creek and Mons Cupri are sufficiently important to warrant description here.

The Whim Creek mine is situated on a stratabound copper-zinc deposit within, and about 100 m above the base of, the Rushall Slate (see Chapter 2). The main ore body occupies the trough of a northeast-plunging open syncline and is confined chiefly between two northeast-striking, sub-vertical faults about 500 m apart; in the main workings, its thickness varies between 10 and 14 m (Reynolds and others, 1975). Rocks above and below the ore horizon are lithologically very similar, but those within the mineralized zone are abnormally heterogeneous consisting of chlorite-rich phyllite, siliceous phyllite, pyritic chert and tuffaceous strata. The northeastern limit of potentially economic ore is 200 m down-dip at a point where the plunge of the syncline steepens from 20-25° to 50°. Total reported reserves are about 132 400 t of oxide ore, containing 4.8% copper, and a possible additional 294 800 t of sulphide mineralization averaging 2.5% at a cut-off of 1% (Reynolds and others, 1975). In order of decreasing abundance, the major sulphides are pyrite, pyrrhotite, chalcopyrite, sphalerite, and galena.

Koehler (1974) and Reynolds and others (1975) considered that the sulphide mineralization is of syngenetic-diagenetic origin and derived from a nearby, exhalative, felsic volcanic centre similar to that at Mons Cupri.

The Mons Cupri mine accounts for 202.81t of the copper production recorded from the Whim Creek centre, most of which was mined between 1899 and 1901 by Balla Balla Copper Mines Ltd; production ceased in 1917. Copper mineralization at Mons Cupri takes the form of disseminated chalcopyrite stockwork, quartz-chalcopyrite veinlets, and rare, massive chalcopyrite lenses in a chloritized felsic agglomerate pipe within the Mons Cupri Volcanics (*see* Chapter 2). Pyrite, galena, and sphalerite are subordinate to chalcopyrite, although the southern margin of the mineralized zone contains up to 3% zinc. Miller and Gair (1975, p. 199) stated that the chloritic pipe is 1 100m long and 250m wide at the top but that it narrows to 25m about 200m below the surface. Miller and Gair also described a stratiform copper-lead-zinc-silver deposit at Mons Cupri. This mineralization occurs in a 3-15m thick unit of tuff and chert which 'caps' the pipe on its northwestern side. Massive sulphides containing chalcopyrite, galena, sphalerite, silver and pyrite are said to be fairly continuous throughout the bed. Finely layered sulphides have colloform and delicate crustification structures.

Marston (1979) quoted total resources (1973) at Mons Cupri as 10.9 to 13.6 Mt of mineralized material (oxidized and primary) averaging 1% copper and 1 Mt of mineralization averaging 2.5% lead, 3.6% zinc and 62 g/t silver. Miller and Gair (1975) suggested that the deposit is of Kuroko or Abitibi type.

YANNERY HILL

The principal mines of the Yannery Hill centre are Whundo and Yannery Hill. Production from the Yannery Hill mine spans the period 1920-1968, but Whundo yielded most of its production in 1976. Both mines exploit copper-zinc mineralization in metamorphosed felsic volcanic or volcanoclastic rocks correlated with the Duffer Formation.

Ore shoots at Whundo mine contain malachite, azurite, and cuprite in the oxidized zone, which grades down into a supergene assemblage of abundant chalcocite plus marcasite, pyrite, neodigenite, sphalerite, covellite, chalcopyrite and accessory native copper. Primary sulphide minerals are pyrite, pyrrhotite, sphalerite, chalcopyrite, and traces of arsenopyrite. The ore bodies are enriched to a vertical depth of about 55 m and appear to be essentially stratabound, occurring in felsic rocks just above an underlying amphibolite unit (correlated with the Mount Ada Basalt).

The rocks at Whundo have undergone greenschist to amphibolite facies metamorphism, which have been overprinted by hornblende hornfels facies contact metamorphism, probably related to a nearby granitic intrusion (Roberts, 1974). Chlorite-muscovite-quartz schist locally contains porphyroblastic andalusite.

In 1976, indicated resources were estimated at 2 Mt of ore containing 2% copper and 1.3% zinc. Total production from Whundo (including the Whundo West mine, 350m distant) has amounted to 7358t of copper ore and 1056t of cupreous ore containing a total of 2013.83t of copper.

The Yannery Hill mine is situated 900m northeast of Whundo. The main workings are concentrated on a stratabound, 1-3m thick ore horizon of chloritic schist in the trough of a northwesterly plunging syncline. Ore minerals are secondary and include malachite, chalcocite and cuprite. Massive limonite is common, but there is little quartz. Country rocks are Archaean quartz-chlorite-sericite schist, unconformably overlain by the Lower Proterozoic Hardey Sandstone.

COPPER HILLS

Of the mines included in the Copper Hills centre (Copper Hills, Copper Hills West, Copper Hills South, and Emu Creek East) only Copper Hills has yielded sufficient copper to warrant special description here.

The Copper Hills mine is centred on an area of disseminated pyrite-chalcopyrite mineralization in felsic tuff and lava of the Duffer Formation. Irregular bodies of felsic porphyry intrude the volcanics, but their genetic relationship to the ore body is uncertain. Malachite, azurite, chalcocite and bornite are concentrated along fractures in the felsic rocks, which are extensively chloritized, epidotized, sericitized and kaolinized. The dominant fracture system strikes northwest, but other sets striking between north and east are also present. The extent of the workings (including several deep pits) indicates a mineralized area 150m long and 50m wide.

Primary mineralization took the form of disseminated sulphides, probably of magmatic-hydrothermal origin. Drilling below the zone of supergene enrichment, which extends to a depth of about 50-60m, has revealed copper concentrations of less than 1%. Between 1954 and 1963, however, the enriched zone yielded 15 455.67t of cupreous ore and concentrates averaging 12.68% copper.

OTHER CENTRES

Marston (1979) gave detailed descriptions of mines and prospects within the other centres listed in Table 10. These descriptions are not repeated here, but the various types of mineralization present at each centre (using Marston's classification) is summarized as follows:

A. STRATABOUND COPPER-ZINC DEPOSITS IN METAVOLCANIC ROCKS
   Copper Gorge, Marble Bar (Big Stubby prospect)

B. STRATABOUND COPPER DEPOSITS IN METAVOLCANIC ROCKS
   Doherty (Otway), McPhee Creek

C. STRATABOUND MINERALIZATION IN MEDIUM-HIGH GRADE METAMORPHIC ROCKS
   Yandicoogina (Lennon Find) Pilgangoora, Egina, Croydon

D. FRACTURE OR QUARTZ VEIN STOCKWORKS
   North Pole (Breens)

E. QUARTZ VEINS AND SHEARS

Felsic host

Glen Ellen Pool (Kelly mine), Marble Bar (7.6km south-southeast)

Metasedimentary host

Middle Creek, Wyman Well, Stinking Pool, Stannum, Mount Berghaus, Snell Well

Mafic-ultramafic igneous host

Lionel, North Shaw, Lalla Rookh (Wilsons), Woodstock, Glenroebourne (Weerianna-Carlow Castle)

Granitic host

Boodalyerrie, Boodarrie, Mount Francisco

STRATIGRAPHIC CONTROL OF MINERALIZATION

Most of the copper deposits in the Pilbara Block occur in felsic volcanic host rocks. Figure 50 demonstrates that mines and prospects are concentrated at one particular stratigraphic level in the Pilbara Supergroup, namely the Duffer Formation. Where the Duffer Formation is absent deposits show a tendency to occur at the same level (i.e. close to the contact between the Towers Formation and the Talga Talga Subgroup). This strong stratigraphic control implies a phase of regional exhalative mineralization at a particular time in the evolution of the supergroup. Copper deposits not occurring at this level show no overall pattern, but are formed in locally favourable geological environments (e.g. Mons Cupri-Whim Creek).

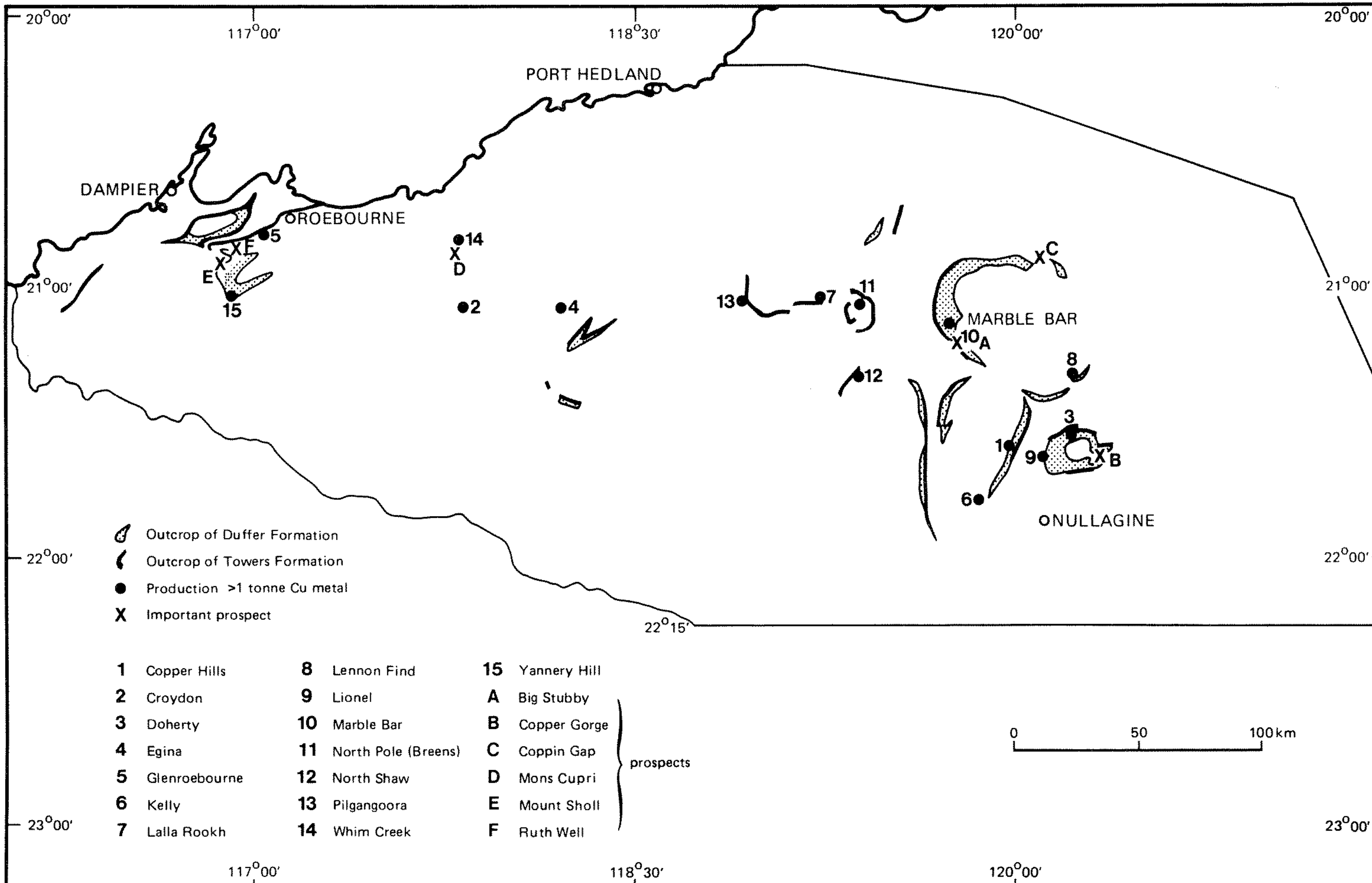
IRON

Iron ore mining in the Pilbara Block commenced in 1966 at Mount Goldsworthy, and the Shay Gap mine was developed a few years later. To 31 December 1980, a total of 85.5 Mt of iron ore grading 64% Fe had been produced. Both mines are centred on supergene enrichment deposits within Archaean banded iron-formation. Because the largest iron ore deposits of the Pilbara region (e.g. Tom Price and Newman) are of Proterozoic age, there has been speculation that the banded iron-formations at Goldsworthy and Shay Gap might not be Archaean. Information gained during regional mapping since 1972, and presented elsewhere in this bulletin, leaves the age of these rocks beyond reasonable doubt. In brief, two main lines of evidence establish that they are Archaean:

(1) the banded iron-formation (Cleaverville Formation) is overlain with a high-angle unconformity by the Hardey Sandstone 10 km south of Yarrie homestead , and,

(2) the succession conformably overlying the Cleaverville Formation at Shay Gap is the same as that in the Gorge Creek Group in the type area.

Other iron ore deposits include Proterozoic hematite conglomerate near Kennedy Gap, and Tertiary pisolitic limonite south of Port Hedland. None of these has yet been mined, but estimated reserves of several million tonnes of low phosphorus ore are available (de la Hunty, 1961a).



GSWA 18146

Figure 50. Plan showing the distribution of principal copper deposits in relation to the Duffer and Towers Formations.

GOLDSWORTHY

In 1963 Mount Goldsworthy Mining Associates announced reserves of 65 Mt of hematite and hematite-goethite ore, containing 54-65% Fe. Descriptions of the deposits are given by Brandt (1964, 1966), Matheson and others (1965) and Neale (1975). The ore of the main deposit is high grade massive, granular, and specular hematite essentially free from deleterious impurities (P, 0.01-0.06%; Sio_2, 0.2-4.0%; Al_2O_3, 0.4-2.5%) and occurs in a 'comformable' lenticular lode, 700 m long, 100 m wide and over 100 m deep. The main pit at Goldsworthy is positioned on the 'No. 1 ore body'. To the south, this deposit is bounded by banded iron-formation and, to the north, by a fault. It is considered to be a Precambrian supergene enrichment of the steeply inclined banded iron-formation protore (Cleaverville Formation).

Other types of iron deposits at Goldsworthy are cappings of supergene hematitite and goethite (generally no more than 30m deep but of considerable lateral extent) and Tertiary detrital deposits.

SHAY GAP

The iron ore deposits at Shay Gap are lenticular bodies of massive hematite several hundred metres long, up to 50m wide and locally over 150m deep. In most respects they are similar to the main ore body at Goldsworthy, although at Shay Gap no folding or faulting is present in the Archaean protore.

OTHER DEPOSITS

Enriched Archaean banded iron-formation occurs in most areas where the Cleaverville Formation crops out. Deposits of this type have been investigated at the Ord Range, Nimingarra, Sunrise Hill, Cattle Gorge, Cundaline Gap, and Strelley Gorge. Published resources (indicated and inferred) are as follows:

Locality	*Resources (Mt)*	*Iron content (%)*
Ord Range	29.5-37	55-56
Nimingarra	44	>60
Sunrise Hill	11.8	(a) >60
Strelley Gorge	8.4	61

(a) Assuming ore grade is similar to that at Shay Gap.

Similar Archaean deposits may yet be found in other areas such as Blue Bar (30km south of Marble Bar), Pincunah, Paddy Market Gorge, and possibly even in the Roebourne-Dampier area. This latter region contains large outcrops of the Cleaverville Formation, but much of the rock is ferruginous chert rather than true banded iron-formation, and no deposits approaching ore grade have yet been detected. Between Cleaverville and Devil Creek, the Cleaverville Formation occupies a continous belt of outcrop-subcrop, and, in view of the proximity of Dampier, the feasibility of geophysical prospecting could be examined.

At Eel Creek, the basal member of the Proterozoic Eel Creek Formation is a hematite conglomerate, (up to 50m thick) composed of sub-rounded clasts (up to 50mm in diameter) of hematite and chert in a ferruginous matrix. Ferruginous siltstone, sandstone and grit are interbedded with the conglomerate, and the unit rests with a high-angle unconformity on steeply inclined Archaean strata. Inferred resources are put at 13 Mt of high-grade ore. Similar beds of ferruginous sandstone and conglomerate occur at the base of the Waltha Woora Formation at Ripon Hills.

The Marra Mamba Iron Formation crops out more or less continuously along the southern slopes of the Chichester Range. Hematite deposits along this outcrop are considered to have formed by Tertiary supergene enrichment of the iron-formation (MacLeod, 1966, p.112) and structural controls are apparently absent. Although locally quite extensive, the deposits are thin and there is generally a rapid deterioration in grade downwards. Zones of high-grade ore rarely extend below a depth of 15m. Sofoulis (1960c) found the grade of surface samples 10km north of Roy Hill homestead to range between 59 and 64%.

The Brockman Iron Formation crops out at Point James, but no ore deposits have been identified. The unenriched banded iron-formation is currently being assessed as potential ore.

Tertiary pisolitic limonite ore deposits occur at Poondano (30km east-southeast of Port Hedland), Ord Range, Lalla Rookh, Abydos, Pincunah, Wodgina and McPhee Creek. Most of these deposits are described by de la Hunty (1961a). The ore is medium grade, but it can be beneficiated by ignition, and it has a low phosphorous content. It is considered to be of the same type and age as that being mined at Robe River. Excluding Wodgina, de la Hunty (1961a, p. 67) estimated that the deposits contain a total of 18 Mt of ore averaging about 56% iron. Blockley (1971a) estimated the largest Wodgina deposit to contain about 1 Mt of ore, and put total resources for the district at 5-10 Mt of pisolite and canga.

LEAD

Lead was first discovered in the West Pilbara Goldfield in 1872 at Andover, but most of the production from the Pilbara Block (Table 11) was mined at Braeside during the period 1925-1959.

BRAESIDE

The Braeside lead field is situated in the northern part of the Gregory Range about 130km east of Marble Bar. Argentiferous galena occurs in quartz veins which intrude strike faults within the Kylena Basalt and the Tumbiana Formation. Almost 3 000 t of lead has come from the Ragged Hills mine. The ore body at this locality is a quartz vein striking 340° and dipping 80° towards the east. Reported ore widths range from 0.6-2.3m in a lode up to 4.2m wide. Lead mineralization extends over 300m along strike and the deposit has been mined to a depth of 50m over a distance of about 150m. The wall rocks of the lode are basalt, tuff, and cabonate rocks. Small amounts of sphalerite accompany the galena, and about 25t of zinc has been produced from the mine.

Other deposits in the Braeside field are similar to that at Ragged Hills, but production has been relatively minor. Detailed descriptions of the various deposits and mines are given by Finucane (1938e) and Blockley (1971b). The origin of the lead has never been established. The fact that the ore bodies are quartz veins and zones of silicification along the area's fault system, shows that mineralization accompanied, or was later than, deformation. The age of this deformation appears to post-date the Waltha Woora Formation which is tentatively assigned to the Middle Proterozoic and certainly is younger than the Carawine Dolomite (between 2600 and 2200 m.y.). Uncertainty as to whether or not the fault system is younger than Lower Proterozoic arises from the superimposition of two phases of deformation with the same structural form and trend (pre-Yeneena Group deformation and deformation of the Paterson Province).

Pb-Pb isotope geochronology (Richards, 1978) suggests that the lead at Braeside is 2700 m.y. old. This rules out the possibility that the veins are hydrothermal emanations from a concealed Upper Proterozoic granitic intrusion of Mount Crofton type; the Mount Crofton Granite (de Laeter and others, 1977) is 600 m.y. old. The most probable explanation is that the lead is derived from Archaean or Lower Proterozoic granitic rocks underlying the Fortescue Group. Such rock may also underlie Miningarra Creek where another quartz-galena vein was discovered in 1974 (Hickman and Chin, 1977).

COMSTOCK

The Comstock lode is situated 6km south-southwest of Whim Creek and immediately south of the Mons Cupri copper mine. Galena, anglesite, cerussite, pyromorphite, malachite and azurite are present within a system of branching and intersecting quartz veins. In the central part of the mineralized area, which crops out over an area of $300m^2$, the veins coalesce to form a relatively rich deposit about 50m long and 10m wide. The host rock of the lead veins is an andesite flow (Comstock Andesite Member) at the base of the Rushall Slate.

ANDOVER

The Andover mine is situated 12km south-southwest of Roebourne and 4km northwest of Andover homestead (Woodbrook). Lead was first discovered at this locality in 1872. Galena occurs in a northerly striking subvertical quartz-pegmatite vein at an intrusive contact between granite and gabbro. Most of the ore was obtained from a pegmatite-rich phase of the vein intruding the granitic rocks.

DOOLENA GAP

In 1955, 4.86t of lead were mined from a quartz-veined fault zone in Archaean metasediments and carbonate rocks at Doolena Gap mine (8km southwest of Eginbah). The carbonate unit may be a completely altered ultramafic rock. The stratigraphic level of the deposit is the central part of the Warrawoona Group. Richards (1978) dated the lead at 3400 m.y.

OTHER DEPOSITS

Numerous lead occurrences have been reported in the Pilbara Block. At Mons Cupri, Miller and Gair (1975) described a layered sequence of tuff and chert, 3-15m thick, which contains massive chalcopyrite, galena, sphalerite and pyrite. The chalcopyrite commonly occurs as cross-cutting veinlets. The ore grade of the beds varies as follows:

Length	*Copper (%)*	*Lead (%)*	*Zinc (%)*	*Silver (g/t)*
2m	0.5	10.9	16.2	171
18m	1.2	5.2	6.5	62

Miller and Gair stated that the bed has plan dimensions of 270m by 400m, implying a total lead content in excess of 200kt. Blockley (1971b, p. 156) stated that an early estimate of resources of 15 Mt of ore containing 4% lead was subsequently found to be too high. Nevertheless the deposit must be viewed as an important lead prospect. Mining will probably depend on market conditions.

Another deposit containing copper, lead, and zinc occurs 6km south of Marble Bar at the 'Big Stubby' prospect. Seven sulphide bodies occur within felsic lava, pyroclastics, and felsic intrusions near the top of the Duffer Formation. Drill hole intersections quoted by Reynolds and others (1975, p. 187) are as follows:

Length	*Copper (%)*	*Lead (%)*	*Zinc (%)*	*Silver (g/t)*
2.52 m	0.1	5.7	21.0	28
1.52 m	0.3	2.9	17.7	84
4.27 m	0.3	3.2	14.7	840

W. Brook (1974) estimated reserves of 0.1-0.2Mt of zinc ore with a grade of 0.23% copper, 4.5% lead, 13.8% zinc, 305 g/t silver, and 20% barite. Sangster and Brook (1977) dated the lead at 3500 m.y. A number of small occurrences of lead ore, some with recorded production, were described by Blockley (1971b). Most deposits in the Pilbara Block occur in felsic volcanic rocks, although the major producer, Ragged Hills mines, is positioned within the Fortescue Group. Copper-lead-zinc deposits are concentrated within the Duffer Formation.

LITHIUM

Potential ore minerals of lithium in the Pilbara Block are spodumene, lepidolite, zinnwaldite and lithiophilite. Pegmatite veins carrying abnormal amounts of spodumene occur at Pilgangoora, or more precisely, 1.5km north of Mount York, where they are up to 25 m wide and contain about 25% spodumene. In 1968, drilling by the Electrolytic Zinc Company of Australasia showed probable reserves of 1.6 Mt of pegmatite containing 1.2% $Li0_2$.

Small amounts of spodumene, lepidolite, zinnwaldite and lithiophilite have been recorded from rare-metal pegmatites at Pilgangoora, Wodgina, Tabba Tabba, Strelley (Ellis, 1950), and most of the other cassiterite and tantalite occurences (Blockley, 1980; Miles and others, 1945; Simpson, 1948, 1951, 1952); no production has been recorded and no economic concentrations are known.

TABLE 11. TOTAL PRODUCTION OF LEAD TO 31 DECEMBER 1977

Centre	Ore and concentrates (t)	Contained lead (t)
Abydos	1.00	0.78
Andover	67.92	44.17
Balmoral	0.60	0.31
Braeside	4 816.51	3 216.60
Comstock (Mons Cupri)	191.53	78.20
Doolena Gap	8.17	4.86
Meentheena	5.63	3.97
North Pole	1.06	0.60
Nunyerry	1.65	1.17
Sundry claims	102.69	50.38
TOTAL	5 196.76	3 401.04

MANGANESE

The Pilbara Region contains substantial deposits of manganese and ferro-manganese ores. Mining commenced in 1954, and to the end of 1977, 1 930 907 t of ore averaging about 50% manganese had been produced. The principal mines are located at Woodie Woodie, Mount Sydney, Ripon Hills, Skull Springs, Mount Cooke and Nimingarra. All these workings except Nimingarra are based on ore bodies in Proterozoic sedimentary rocks; the Nimingarra mine exploits a Tertiary deposit. Inferred resources of ore with an average manganese content of greater than 40 per cent are currently estimated to be just over 4 Mt, the bulk of which occurs at Ripon Hills and Woodie Woodie.

The Proterozoic manganese deposits are irregular bodies resulting from supergene replacements of shale or dolomite, or residual concentrations in chert breccia (itself a product of replacement). The manganese appears to have been derived from manganiferous shale and dolomite belonging to the Hamersley and the Bangemall Groups. Within the Hamersley Group a 2-3m thick manganese-rich shale occurs near the top of the Marra Mamba Iron Formation across the greater part of the Hamersley Basin (Blockley, pers. comm.). The average manganese content of this unit is only about 5 per cent, but in places it is significantly enriched and thickens to about 30 m. Another potential source of manganese is the Carawine Dolomite which contains up to 2.9 per cent MnO (de la Hunty, 1963, p. 41). Solution of such a rock, as occurred over wide areas of the east Pilbara during the Proterozoic, could produce large manganese deposits in areas of restricted drainage. Davy (1975) reports manganese of up to 2.5 per cent in carbonate units within the Mount McRae Shale where manganese is present as mangano-siderite. A fourth source of manganese lies in the manganiferous shales of the Manganese Subgroup (part of the Bangemall Group, Muhling and Brakel, in press). The Noreena Shale contains between 0.43 and 10.3 per cent Mn and the Balfour Shales between 0.03 and 13.2 per cent Mn (de la Hunty, 1963, p.41). The Balfour Shale is 450m thick and the Noreena Shale about 30m thick.

Mining centres which have produced manganese (Table 12) were fully described by de la Hunty (1963). In addition, the Ripon Hills ferro-manganese deposits were described by Campana and others (1972) and Denholm(1977), and de la Hunty (1965b) presented further details of the manganese deposits at Woodie Woodie and Mount Sydney. Because of these available references, only the larger deposits are briefly discussed below.

RIPON HILLS

The main group of ferruginous manganese deposits at Ripon Hills is clustered in an area measuring approximately 6 by 5km. During 1971 and 1972 Longreach Metals N.L. investigated the deposits by geological mapping, drilling and bulk beneficiation testing. The ore is composed of fine-grained pyrolusite intergrown with hematite and locally contains altered bixbyite and braunite (Denholm, 1977). The principal gangue is kaolin. Denholm reported inferred reserves of 56 Mt with an average grade of 19.4 per cent manganese and 25.9 per cent iron, (based on a cut-off grade of 15 per cent manganese). The beneficiation programme indicated that if specification ferruginous manganese ore (28 per cent manganese and 16 per cent iron) was to be obtained, a cut-off grade of 20 per cent manganese should be used. Inferred reserves of such ore are put at 12 Mt.

The deposits occur within shale of the Waltha Woora Formation and immediately overlie, or pass downwards into, the Pinjian Chert Breccia. According to Denholm (1977) the shales exhibit all stages of replacement by iron and manganese oxides, and the ore varies from hard and massive to friable and shaley.

About 10km to the south of the ferro-manganese deposits, manganese ore has been mined from the Carawine Dolomite. Production appears to have been bulked with that from other areas.

WOODIE WOODIE AND MOUNT SYDNEY

The Woodie Woodie-Mount Sydney area is credited with production of 1 337 856 t of manganese ore although a minor proportion of this was probably obtained from nearby centres such as Ripon Hills and Skull Springs (location records are incomplete). At Woodie Woodie, the manganese ore generally occurs in cappings on, or fissures in, the Carawine Dolomite or the Pinjian Chert Breccia. The principal ore body appears to be a cave filling. The main ore body at Mount Sydney is located on a fault through the Carawine Dolomite, and was probably precipitated by solutions carrying manganese along the zone of weakness. Joints in the vicinity of the fault also contain manganese accumulations. Inferred resources of the Woodie Woodie area are estimated to be about 8 Mt of ore containing over 40 per cent manganese.

MOUNT COOKE

Deposits around Mount Cooke and Ant Hill have yielded 562 657.20 t of ore with an average grade of 49 per cent manganese. At Ant Hill manganese ore is interlayered with shale of the 'Manganese Subgroup', and also occurs in breccia which caps the hill. One of the quarries exposes a 15 m high face containing medium-grade manganese ore and a few shaley bands; the ore body crops out continuously for 150 m with a maximum width of 30 m (de la Hunty, 1963, p. 79).

NIMINGARRA

Between 1959 and 1962 some 19 661 t of massive colloform and pisolitic pyrolusite were quarried from Tertiary duricrust 11 km northeast of Nimingarra homestead and

55 km east of Goldsworthy. The average grade of this ore was 44 per cent manganese, and Hickman (1977a) put inferred resources of similar material at about 50 kt. The deposits overlie Archaean banded iron-formation and are probably of similar origin to laterite and pisolitic limonite cappings developed elsewhere in the Pilbara Block.

TABLE 12. TOTAL PRODUCTION OF MANGANESE TO 31 DECEMBER 1977

Centre	*Manganese ore (t)*
Mount Cooke	562 657.20
Mount Nicholas	3 642.85
Mount Sydney	1 282 296.24
Nimingarra	19 660.91
Nullagine	7 089.97
Woodie Woodie	55 559.99
TOTAL	1 930 907.16

MOLYBDENUM

Molybdenum ores have not been mined on any appreciable scale in Western Australia, although small deposits of the metal have been worked or reported in various parts of the State. In the past, most mines were on the Yilgarn Block, in quartz-rich veins associated with granitic rocks, but recent exploration in the eastern part of the Pilbara Block has located disseminated deposits associated with granodiorite at Coppin Gap and Wallabirdee Ridge. The Coppin Gap molybdenum-copper prospect is situated 1.5 km southwest of Coppin Gap in mafic to felsic volcanic rocks close to the northern margin of the Mount Edgar Batholith. To the north of the volcanics, a narrow belt of altered peridotite intrudes the Bamboo Creek-Pear Creek dislocation (Chapter 2). North of this ultramafic is a prominent ridge of BIF with minor sandstone.

Mineralization at Coppin Gap occurs in a stockwork of quartz-carbonate veins (with or without chlorite, potash feldspar and biotite) carrying up to 2 per cent chalcopyrite, molybdenite, pyrite, pyrrhotite, and rare sphalerite and scheelite. This stockwork may be genetically related to a concealed intrusion of granodiorite which has been intersected in drilling. As this granodiorite is so close to the intrusive contact of the batholith, it can be assumed to be a local protuberance. Similar intrusions crop out within the greenstones between Coppin Gap and the Talga River 30 km to the west. Molybdenum and copper concentrations are highest where the granodiorite intrudes the felsic and intermediate volcanics. Drilling by Australian Anglo American Ltd during the period 1970-1973 intersected grades of 0.23 per cent copper and 0.13 per cent molybdenum over 75.6 m. Esso Exploration and Production Australia Inc. have tested the prospect, and have dated the intrusive rocks (granodiorite and associated dacite porphyry) as clearly Archaean (2 915 $\pm$ 207 m.y., J. R. de Laeter, pers. comm.).

In the area south and southeast of Wallabirdee Ridge company exploration has revealed copper-molybdenum mineralization associated with granodiorite and felsic porphyry intrusions within the Salgash Subgroup. Chalcopyrite and molybdenite occurs chiefly in fractures close to the margins of the intrusions. Molybdenite is visible in surface exposures, but the grade of the deposits is considered to be too low to warrant development.

Simpson (1952, p. 241) noted minor occurrences of molybdenite in pegmatite and granitic rocks at Eley, Mount Francisco and Wodgina; all appear to be of interest merely as specimens. Ellis (1962) referred to the presence of powellite (calcium molybdate) at Mount Hall.

NICKEL

Despite extensive exploration by many companies, no economic deposits of nickel have yet been discovered in the Pilbara Block. The only sizeable deposit is at Sherlock, where reserves of 76 Mt averaging 0.5 per cent nickel are reported, but this grade is well below present commercial requirements. Other low-grade deposits occur at Ruth Well, Mount Scholl and Bamboo.

SHERLOCK

The Sherlock nickel sulphide deposit is situated between the Sherlock and Little Sherlock Rivers 40 km east of Roebourne. Nickel-copper mineralization occurs in quartz-magnetite-amphibole schist within Archaean volcanic rocks close to the northern margin of the Caines Well Granite. In outcrop, the ore zone resembles sheared iron-formation, but Miller and Smith (1975) stated that stratigraphic, structural and petrographic studies indicated that it fills a fracture zone and is essentially intrusive. Nickel and copper are considered to have been derived from a nearby serpentinite (altered peridotite) and talc-chlorite-calcite schist. Nickel mineralization is primarily confined to a 2 km long zone within which the ore body extends to a depth of 1 000 m. The main deposits strike west, dip 85° north, measure about 40 m in width and contain pyrite, pyrrhotite, and pentlandite and chalcopyrite. One intersection returned an average grade of 0.6 per cent nickel over 25 m. Wall rocks include andesitic ash flow tuff, basalt, rhyolite and microgabbro.

The nickel-copper deposits at Sherlock are situated on a major crustal fracture extending from Peawah Hill to Mount Oscar. Farther west this fault merges with, or continues as, the Mount Sholl Shear Zone. Mineralization is probably associated with locally intensive deformation of the ultramafic rocks.

RUTH WELL

In 1971 Whim Creek Consolidated N.L. announced high-grade nickel-copper mineralization at Ruth Well, 30 km west-southwest of Roebourne. One diamond drill hole had intersected rock containing 7.2 per cent nickel and 5.35 per cent copper over 5 m at 60 m depth, and 3.22 per cent nickel and 2.26 per cent copper over 5 m at about 50 m depth. A second hole contained 3.1 per cent nickel and 0.60 per cent copper over 10 m at 60 m depth. Numerous other holes failed to intersect significant mineralization.

The Ruth Well nickel-copper deposits occur in ultramafic and mafic extrusive rocks within the Talga Talga Subgroup. Tomich (1974) stated that the main zone of mineralization occurs near the top of an ultramafic extrusive sequence and that it takes the form of a disseminated matrix and massive sulphides underlain by a massive magnetite zone. This magnetite zone contains pentlandite, violarite, pyrrhotite, chalcopyrite, and pyrite, together with rarer arsenides and sulpharsenides. These minerals occur in an antigorite-tremolite-chlorite-talc-carbonate rock possessing a chemistry (Tomich, 1974, Table 13) consistent with it having originally been a peridotitic komatiite (spinifex textured ultramafic flows are locally common in the succession). The principal ore body is cylindrical and plunges east-northeast at about 30°, an orientation which coincides with the plunge of local minor folds, and probably also with that of the Roebourne Syncline (2 km to the north).

Tomich (1974, p. 80) concluded that the deposit is the result of metamorphism on pre-existing magmatic sulphide-oxide accumulations in the extrusive rocks.

MOUNT SHOLL

Shortly after releasing news of the Ruth Well deposits, Whim Creek Consolidated N.L. announced nickel-copper mineralization at Mount Sholl, about 7 km to the south. The main deposits were stated to extend over an area 500 m long and 120 m wide. One diamond drill hole intersected rock containing 1.08 per cent nickel and 1.21 per cent copper over 22 m, and another hole found 0.5 per cent nickel and 0.65 per cent copper over 45 m.

The Mount Scholl mineralization is in a layered gabbro-norite-pyroxenite-peridotite body (Chapter 2) which intrudes the contact between the Talga Talga Subgroup and the Duffer Formation 4 km northwest of Mount Sholl. Disseminated pyrrhotite, chalcopyrite and pentlandite deposits occur along the northwestern margin of the intrusion, which structurally represents its base. At the northeastern end of the intrusion surface, mineralization is visible as copper-stained limonitic meta-peridotite exposed in shallow costeans, but the main deposits have no obvious surface expression.

BAMBOO CREEK MINING CENTRE

Nickel mineralization at Bamboo Creek takes the form of disseminated gersdorffite in silicified and brecciated metadolomite. Drilling by Woodsreef Mines Limited (Pratt, 1971) resulted in an intersection of 0.96 per cent nickel over 15 m. Nickel concentrations between 0.61 and 1.70 per cent were encountered in other sections, but the mineralized zones were generally only a few metres wide.

The Bamboo Creek nickel deposit is situated between the Mount Prophecy and Prince Charlie gold mines at depth of 150-200 m. Nickel is concentrated near the contact between metadolomite (interpreted as a carbonatized ultramafic rock) and chlorite-dolomite schist. This contact and associated breccia zones are considered to be strike faults inclined steeply northeast. The deposits probably originated through deformation and metamorphism of a magmatic accumulation of nickel sulphides within the ultramafic unit. If this is so, similar deposits might occur along strike.

OTHER DEPOSITS

Nickel-copper sulphide mineralization is known to exist in the Munni Munni Complex (Donaldson, 1974) and at Soanesville, but these deposits appear to be subeconomic. Disseminated nickel mineralization occurs in peridotite units of the Pilbara Block, but grades rarely exceed 0.5 per cent, and no large low-grade deposits have yet been identified. Apart from the layered complexes, the most prospective rocks may lie in the fault zone between Bamboo and Pear Creek. A gossan at Pear Creek was found to contained 0.68 per cent nickel and 0.53 per cent chromium.

SILVER

In the Pilbara Block, 1 356.66 kg of silver has been produced as a by-product of gold, lead and copper mining (Table 13). Numerous centres have contributed to this total and the only significant producer is Braeside, which is described in the Section on Lead.

Stratiform to stratabound copper-lead-zinc-silver deposits occur at Marble Bar, Mons Cupri, and Lennon Find. The Marble Bar (Big Stubby) and the Mons Cupri deposits are described in the Sections on Lead and Copper respectively. The Lennon Find deposits are 7 km northeast of Yandicoogina gold mining centre and consist of stratiform, lenticular bodies within fine-grained quartz-sericite schist, talc-sericite schist and calc-silicate rocks of the Duffer Formation. These rocks are sheared and intruded to the northwest by the Mount Edgar Batholith. The main ore horizon

TABLE 13. PRODUCTION OF SILVER TO 31 DECEMBER 1977

Centre	*By-product of gold mining (kg)*	*By-product of lead mining (kg)*	*By-product of copper mining (kg)*
Abydos Station	—	0.19	—
Andover	—	13.74	—
Balmoral	—	0.06	—
Bamboo Creek	94.10	—	—
Braeside	—	919.00	—
Comstock	—	27.75	—
Copper Hills	—	—	14.51
Doolena Gap	—	1.37	—
Eastern Creek	0.95	—	—
Lalla Rookh	17.32	—	—
Lionel	—	—	1.54
Lower Nickol	0.03	—	—
Marble Bar	42.05	—	—
Meentheena	—	0.46	—
Middle Creek	2.13	—	—
North Pole	61.25	0.27	—
Nullagine	3.70	—	—
Nunyerry	0.37	—	—
Pilgangoora	0.17	—	—
Roebourne	15.46	—	0.59
Shark	0.88	—	—
Talga Talga	0.02	—	—
Twenty Mile Sandy	11.23	—	—
Warrawoona	0.78	—	—
Weerianna	0.04	—	—
Whim Creek	—	—	26.51
Wodgina	0.10	—	—
Wymans Well	0.30	—	—
Yandicoogina	1.43	—	—
District Generally	83.36	—	15.10
TOTAL	335.67	962.84	58.25

extends 4 km along strike and has been worked for copper in five places (Blockley, 1971b). Most of the ore bodies are between 0.3 and 1.3 m thick and contain about 600 g/t silver.

Data available on the Mons Cupri deposit (Miller and Gair, 1975) indicate that it probably contains the largest reserves of silver in the Pilbara Block (perhaps as much as 200 t).

TANTALUM AND NIOBIUM

Table 14 shows that mines in the Pilbara Block have produced over 900 t of tantalite concentrate and 82 t of tantalite-columbite concentrate. Almost 50 per cent of Western Australia's total production of these concentrates has come from this area.

The main primary source of tantalite and columbite in the Pilbara has been pegmatite (Chapter 2). Although Cooglegong has recorded the highest production of concentrates, the grade of this material was exceptionally low, about 2 per cent Ta_2O_5: reflecting the lack of suitable concentrating methods available at the centre. The principal sources of tantalite-columbite minerals have been Wodgina, Tabba Tabba, Strelley, Cooglegong, Pilgangoora, and Eley; Pilgangoora has produced 14.63 t Ta_2O_5 from 33.31 t of concentrate whereas Cooglegong has produced only 11.60 t Ta_2O_5 from 466.32 t of concentrate.

WODGINA

The total production of Ta_2O_5 from Wodgina is not officially recorded but an estimate of 140 t is reasonable on the basis of the prices obtained for the concentrate, and on assays over a period of years.

Production recorded under the Wodgina mining centre has been obtained from Wodgina, West Wodgina and Stannum. The main tantalite deposit is situated about 1 km northeast of the old Wodgina townsite on MC 107. Referred to as the 'Tantalite Lode', this deposit is a pegmatite vein striking north, dipping 40° east and extending for about 700 m. Its true width varies from 3 to 10 m, and it intrudes actinolite amphibolite. The pegmatite is composed of a granitic-textured core with marginal and cross-cutting veins of almost pure albite.

Irregularly distributed bunches of quartz, microcline, lepidolite and pale-green mica are also present. Manganotantalite is distributed sporadically throughout the lode but is concentrated in the feldspathic portions. In the early days of mining, some very large pieces of the mineral were extracted; Maitland (1908, p. 274) recorded that one piece mined in 1905 weighed about 250 kg, and fragments up to 2 kg in weight were commonplace. More details of this and other deposits at Wodgina are given by Miles and others (1945, p. 29) and Finucane and Telford (1939a).

TABBA TABBA

Tabba Tabba mining centre appears to have produced between 15 and 20 t of Ta_2O_5 (as at Wodgina, the tantalum content of concentrates is only partly recorded). The principal deposit is a 600 m long pegmatite, the width of which ranges from 10 to 50 m. The pegmatite intrudes amphibolite and is coarsely crystalline containing albite, quartz, beryl, manganotantalite, manganocolumbite, cassiterite, simpsonite, and microlite. Mineralization is restricted to narrow zones of aplitic albite pegmatite bordering large masses of sheeted quartz. The aplitic zones are finely layered with tantalite and beryl occurring in a regular sequence away from the quartz (Ellis, 1950). Other pegmatites at Tabba Tabba contain appreciable amounts of lepidolite and spessartine (Blockley, 1980).

STRELLEY

About 15 t of Ta_2O_5 have been produced from the Strelley mining centre where a large pegmatite dyke intrudes pelitic schist, ferruginous chert, serpentinite and amphibolite. The dyke is broadly stratiform and trends north-northeast close to the eastern margin of the Indee Syncline. It crops out over a distance of 700 m and is between 25 and 200 m wide. Quartz, microcline and mica are the principal mineral constituents. The workings, now largely filled in, consist of scattered pits and trenches, none of which have penetrated more than about 6 m into the intrusion.

Manganotantalite, lepidolite, beryl, and small amounts of cassiterite, microlite, tapiolite, and lithiophyllite are restricted to greisen lenses within the pegmatite, or to zones where fine-grained albite has replaced microcline pegmatite in the form of stockworks. Most of the tantalite production has been obtained from colluvium on either side of the lode.

PILGANGOORA

Large pegmatite bodies intrude amphibolite facies metabasalt and metamorphosed ultramafic rocks at Pilgangoora. The area is situated on the western margin of the Pilgangoora Belt, and granitic rocks of the Carlindi Batholith underlie the country to the west. The pegmatites occupy a 5 km long north-south zone; individual masses are up to 600 m in length and 300 m wide. Despite their large sizes the pegmatites are quite sparsely mineralized. Economic minerals are restricted to parts of the veins where the normally barren quartz-microcline-biotite pegmatite is altered to quartz, albite, muscovite, spessartine, and varying amounts of lepidolite, spodumene, tantalite, columbite, cassiterite, and traces of microlite, tapiolite and beryl. Mineralization is concentrated at the margins of the veins. Of five groups of shallow pits sunk on the veins, four were principally for tantalite.

As at Strelley, much of the tantalite production recorded from Pilgangoora was obtained from alluvium and colluvium. The tantalum content of the Pilgangoora ore varies considerably, ranging from good grade manganotantalite down to manganocolumbite and ferrocolumbite. Samples assayed (Miles and others, 1945, p. 35) range from 24 to 53 per cent Ta_2O_5 and from 30 to 56 per cent Nb_2O_5.

In 1968 Ishihara Sangyo Kaisha Ltd sampled about 30 creeks and gullies in the area. Using a cut-off grade of 0.06 kg/m^3 of Ta_2O_5, reserves of 288 000 m^3 of alluvium containing an average of 0.22 kg/m^3 Ta_2O_5, 0.10 kg/m_3 Nb_2O_5 and 0.10 kg/m^3 SnO_2 were established.

COOGLEGONG

During 1968 and 1969, 466.32 t of low-grade tantalite concentrates were sold from the Cooglegong area of the Shaw River tin field. This material represented an accumulation of 'second' concentrates produced during tin mining operations. The pegmatites of the Cooglegong area are not noted for their tantalite content; most are layered albite pegmatites. According to Miles and others (1945) the main tantalum- and niobium-bearing minerals at Cooglegong are fergusonite and tanteuxenite.

ELEY

Production of by-product tantalite from tin mining in the Eley centre has amounted to 8.55 t of Ta_2O_5 from 81.65 t of concentrate. The geology of the Eley area is similar to that at Cooglegong, but the main tantalite mineral is reputed to be tanteuxenite, with microlite, yttrotantalite and calciosamarksite also being recorded (Miles and others, 1945, p. 36).

MOOLYELLA

Tantalite has also been obtained as a by-product of tin mining at Moolyella where the primary source is layered albite pegmatites. Production figures show that 3.84 t of Ta_2O_5 have been produced from 14.06 t of concentrate, and 0.80 t of $(Ta, Nb)_2O_5$ from 1.29 t of mixed concentrate.

OTHER AREAS

Total production of Ta_2O_5 from areas other than those described above amounts to only 4.8 t most of which has been recorded in the category 'District Generally'. Tantalum- and niobium-bearing ore was first recorded at Mount Francisco in 1906, and minor production (0.32 t Ta_2O_5) is recorded from pegmatites which intrude ultramafic and mafic schist. Abundant manganocolumbite occurs in a pegmatite vein 7 km east of Francisco Well. The positon of this deposit, referred to as 'Hooleys Columbite Lode' (Simpson, 1927), has never been firmly established, but it may be the Numbana mine. A zoned, quartz-cored pegmatite, about 15 m in length, intrudes the Numbana Granite at this locality. Production during the period 1953-1956 amounted to 2.6 t of $(Ta, Nb)_2O_5$ from 3.5 t of concentrate. Other minerals in the pegmatite include mica and beryl. Microcline pegmatite dykes at the Pippingarra mining centre have yielded 2.61 t of $(Ta, Nb)_2O_5$ from 3.60 t of tantalite-columbite and 0.63 t Ta_2O_5 from 3.09 t of tantalite concentrate. The pegmatite bodies are several tens of metres wide and extremely coarse textured. Lenses of muscovite over 1 m wide and several metres long are quite common, especially in the eastern workings. About 2.4 t of $(Ta, Nb)_2O_5$ has been obtained from concentrates at the Upper Five Mile centre 17 km southeast of Nullagine. De la Hunty (1964) stated that the locality also contains beryl. Production was from alluvial workings, although small pits have been cut into pegmatites associated with the Bonney Downs Granite. Layered albite pegmatites close to the margin of this pluton have been worked 27 km to the southeast of Upper Five Mile at Haystack Well. No production figures are recorded.

At Mount Hall, 4 km southeast of Roebourne, pegmatite veins which intrude serpentinite and metagabbro have yielded tantalite and tantalite-columbite concentrates (Table 14). These contained 1.04 t Ta_2O_5 and 2.46 t $(Ta, Nb)_2O_5$. Some of the pegmatites show a crude zoning, quartz cores being surrounded by layers of quartz, cleavelandite (albite) and muscovite, together with beryl, zinnwaldite, cassiterite, tantalite and prehnite. Most of the production appears to have been from alluvium. Over 100 t of beryl were obtained from the deposits, and 1.10 t of tin concentrate were also mined.

Mines Department records show that about 3 t of tantalite-columbite concentrate were mined from Pastoral Creek which is situated about 15 km east-southeast of Wodgina and drains the northern part of the Numbana Granite. Alluvium in the creek has been worked over a length of 200 m; the ore was presumably being derived from pegmatite similar to that at Numbana.

TABLE 14. TOTAL PRODUCTION OF TANTALITE AND TANTALITE-COLUMBITE CONCENTRATES TO 31 DECEMBER 1977 (a)

Centre	*Tantalite concentrate (t)*	*Tantalite-columbite concentrate (t)*
Abydos	0.08	
Cooglegong	466.32	0.09
Eley	81.65	
Hillside	0.17	
Kangan Station	0.05	
Moolyella	14.06	1.29
Mount Francisco	2.05	1.78
Pilgangoora	33.31	13.10
Pippingarra	3.09	3.60
Roebourne	3.34	5.26
Shaw River	0.12	
Strelley	(a) 29.95	
Tabba Tabba	27.04	0.26
Trigg Hill (Cooglegong area)	0.38	
Twin Sisters	0.16	
Upper Five Mile Creek		3.67
Wodgina	(b) 243.15	10.47
Crown lands	0.56	

(a) Ta_2O_5 content ranges from 2 - 60 per cent (records are incomplete).
(b) Incorporates data from Kalix and others (1966).

TIN

Production of cassiterite concentrate from the Pilbara Block to the end of 1977 totalled 15 942.68 t (Table 15) which has realized some $18.5 million. Mining operations are currently in progress at Moolyella, Shaw River, and Friendly Creek.

The more important cassiterite deposits are related to the post-tectonic granitic plutons (Blockley, 1970). The only significant production of primary tin ore came from the Wodgina centre where albite pegmatite and associated tourmaline lodes were mined in the early part of the century to yield about 380 t concentrate. Secondary concentrations of cassiterite are found in alluvium and eluvium close to outcrops of cassiterite-bearing pegmatite. Deposits of buried alluvium at Moolyella, Cooglegong and Eley have accounted for about 90 per cent of the total production. Blockley (1980) presents a detailed description of the area's tin deposits, and the following account is essentially a summary of his findings.

MOOLYELLA

The Moolyella tin field extends across an area of 100 km² and is centred about 20 km east of Marble Bar. According to Maitland (1904), the field was discovered in 1898, in which year 76.5 t of concentrate were obtained. The principal workings are grouped close to a range of low craggy hills at the head of Moolyella Creek. Buried alluvial channels radiating from the base of the hills carry concentrations of cassiterite,

TABLE 15. PRODUCTION OF TIN CONCENTRATE TO 31 DECEMBER 1977

Field or Centre	*Tin concentrate (t)*	*Realised value (Aust $)*
Coondina	613.36	1 471 637
Friendly Creek	119.82	316 710
Moolyella	7 798.06	10 101 710
Pilgangoora	13.71	15 102
Pinga (Abydos)	42.18	104 373
Shaw River	6 584.33	7 123 203
Tabba Tabba	131.92	32 103
Wodgina	478.01	114 617
Minor Centres and Sundry Claims	161.29	334 732
TOTAL	15 942.68	19 614 187

generally in coarse gravel bound by green, or greenish-yellow, puggy clay. Above this coarse material, which generally occurs in the lower metre or so of each channel, are finer deposits, in which the matrix is reddish and less plastic. This finer material is poorer in tin and normally discarded as overburden during mining operations. The contact between the two types of alluvium is generally sharp and has been used by the miners to indicate the top of 'pay dirt'. Early mining methods were more selective than those employed today, and Montgomery (1907) quoted a minimum grade of 16 kg/m³ on MacDonald's Lead (previously called Prospectors Creek); he (Montgomery, 1907, p. 78) also stated that workings on Moolyella Creek had exposed a channel 60 m long and 6-12 m wide which contained more than 11.5 kg of tin concentrate per tonne of dirt. Cut-off grades currently used on the Moolyella tin field range from 0.9 to 1.2 kg/m³. The depth of the buried channels is invariably less than 10 m below the surface and averages 2-3 m; channel widths generally range from 10-30 m.

In 1968, Pilbara Tin Pty Ltd estimated ore resources to be 520 000 m³ of ore containing 1 725 t of tin oxide. Much of this has since been extracted. Two years later, Metramar Minerals Ltd published reserves of 1.76 x 10^6 m³ averaging 1.67 kg/m³ tin oxide, a figure apparently not substantiated by later work.

Cut-off grades used to date are high because of difficulties in treatment (e.g. lack of plentiful supplies of water) and the irregular distribution of the deposits. The material which makes up the bulk of the resources is situated in extensions of the known deep leads beneath presently uneconomic depths of overburden, lower grade alluvial deposits on the fringes of the tin field, overburden dumps, and tailings from the treatment plants.

Figures provided by Pilbara Tin Pty Ltd indicate that about 2 x 10^6 m³ of untreated overburden will remain after the existing ore reserves are mined. The average grade of these dumps is estimated to be 0.3-0.6 kg/m³ tin oxide. Portions of four tailings dumps sampled by Ishihara Sangyo Kaisha Ltd contained between 0.8 and 1.25 kg/m³ tin oxide. Many of the tailings produced in the 1950s and early 1960s have been re-treated with good results.

The origin of the cassiterite in the Moolyella deep leads has been traced to layered albite pegmatite dykes which occupy northerly striking tension fractures close to the post-tectonic Moolyella Adamellite. The cassiterite content of the pegmatites varies considerably, and in only a few places is it high enough to have encouraged mining. Lode tin was mined from MC 815 which covers a pegmatite dyke at the edge of the post-tectonic intrusion. Blockley (1980) states that 480 t of ore averaging 0.3 per cent tin concentrate were obtained. Other veins and dykes have yielded smaller tonnages of ore. In most of the primary deposits cassiterite is concentrated near the margins of the pegmatites.

SHAW RIVER

Blockley (1980) groups a number of geologically related mining centres near the Shaw River under the heading of the 'Shaw River tin field'. This field covers an area of 1 200 km^2 and includes the mining centres of Cooglegong, Eley, Five Mile Creek, Tambourah Creek, Split Rock, Coomba Creek, and Hartigan Creek. Simpson (1948) stated that tin was discovered in the area by Mr A. Eley in 1890.

As at Moolyella, virtually all the tin obtained from the Shaw River tin field has been mined from alluvium. A large post-tectonic pluton, the Cooglegong Adamellite, intrudes the Shaw Batholith in this area and layered albite pegmatites associated with it have shed cassiterite into deep leads (generally less than 3 m below the surface) similar to those at Moolyella. Lode tin has been mined at one locality only, Stutz's P.A., 1.8 km southeast of Spear Hill.

About 75 per cent of the field's production was obtained from the Cooglegong mining centre, most of the remainder coming from Eley. Most of the prospective ground at Cooglegong has been treated, and it is now difficult to estimate the original widths and depths of the tin-bearing wash. The diggings at Two Mile Creek are the largest in the mining centre. They extend for 5.5 km along Two Mile Creek and include a number of tributary streams. The main creek bed was mined out over widths of 20-60 m, and to depths of 1.5-2.5 m. The thickness of the pay dirt is stated to have been about 1 m.

Reserves and grades of tin concentrate in the Shaw River tin field are discussed by Blockley (1980). Extensive testing of the area indicates little chance of finding large new economic deposits, although recent rises in the price of the metal could justify a future reassessment. Easily accessible resources now appear to lie in the dumps of overburden and tailings. The tailings dump at Johnston's plant at Eley contains 53 500 m^3 of material with about 0.9 kg/m^3 tin oxide (Blockley, 1980).

COONDINA

Most of the 613.36 t of tin concentrate produced from Coondina were mined from clay and carbonate-cemented alluvium occupying an old stream channel which runs parallel to the Shaw River. The deposit is 2 km long, 45 to 75 m wide, and has a maximum thickness of 4.3 m. The richest ore occurs at the base of the channel, where cemented or silicified grit and gravel contains up to 30 per cent by volume of cassiterite. This rich ore is generally only a few centimeteres thick and is overlain by poorer, though also tin-bearing, alluvium, made up of quartz, granite and pegmatite set in a matrix of white clay and cemented by varying amounts of carbonate. Cassiterite grains range from 0.5 to 5 mm in diameter, and average about 2 mm.

The cassiterite grains and rock clasts in the alluvium are derived from layered albite pegmatites associated with a post-tectonic intrusion (the Coondina Adamellite), which crops out 3 km to the south.

The cemented alluvium is overlain by high-level gravel of the Yule Surface, and Blockley (1980) considers that it is probably of Tertiary age. The Quaternary gravels and recent alluvium at Coondina also contain tin, but grades are generally low, except in those narrow gullies mined in about 1966-1967.

WODGINA

The Wodgina tin field includes the mining areas of Wodgina, West Wodgina, Stannum, Mills Find, Numbana and Mount Francisco. With the exception of Numbana, the deposits are associated with pegmatite bodies which intrude greenstones. In this respect the geology of the Wodgina field differs markedly from that of those discussed above.

Most of the production noted in Table 15 came from the Mount Cassiterite mine at Wodgina—the largest underground tin mine in Western Australia. Albite-quartz pegmatite containing cassiterite, tourmaline, beryl, tantalite, and lithium minerals intrudes ferruginous chert at this locality. According to Blatchford (1913), cassiterite was distributed throughout the pegmatite lode, but was concentrated near its margins. Large blocks of cassiterite mined from the footwall are said to have weighed up to 110 kg. The width of the main lode ranged from 1.2-4.2 m and averaged 1.5 m. Numerous smaller workings at Wodgina are described by Blockley (1980). Alluvial cassiterite has been obtained from gullies that drain the areas veined by pegmatite.

At West Wodgina, simple or zoned pegmatite veins, containing cassiterite, lepidolite, garnet and tourmaline, intrude amphibolite schist, ultramafic rock and siliceous metasediment (Blockley, 1980). Production has amounted only to a few tonnes of concentrate. The Stannum group of tin mines accounts for at least 11.1 t of the Wodgina field's total production of tin concentrate; the actual production was probably greater (Blockley, 1980). Pegmatite at the Stannum mine carries up to 5 per cent cassiterite, accompanied by columbite, lepidolite, blue tourmaline and topaz. The veins are less than 1 m wide and dip southwards at low angles.

According to Blockley (1980) Mills Find is 11 km southwest of Wodgina and 3 km southwest of Stannum in an area underlain by amphibolite and intruded by granite and pegmatite. One parcel of ore is said to have yielded 0.7 t of concentrate from 20 t of pegmatite, a grade of 3.5 per cent tin oxide.

The Mount Francisco tin deposits occur within a large roof pendant of ultramafic schist, amphibolite and metasediment intruded by the Numbana Granite. The pegmatites of this area contain cassiterite, tantalite and beryl.

OTHER AREAS

The Friendly Creek tin deposits occur in Recent and Tertiary alluvium. Most production prior to 1971 came from the bed of Middle Creek, an east-flowing tributary of Friendly Creek. Tertiary alluvium has been tested by costeaning and drilling. It has a depth of 3-15 m and covers an area of 10 ha; in most respects it resembles the Tertiary deposit at Coondina. On the eastern side of Friendly Creek, the deposit is estimated to contain reserves of 684 000 m^3 averaging 2.8 kg/ m^3 of tin concentrate (Blockley, 1980). Farther west another section of the unit contains inferred resources of 350 000 m^3 holding 1-1.5 kg/ m^3 of tin oxide. The tin at Friendly Creek is derived from layered albite pegmatites thought to be related to a stock of massive post-tectonic granite (Plate 1A).

Tin and tantalum produced from the Tabba Tabba centre was mined from albite pegmatite veins which intrude amphibolite and minor metasediments. The veins are about 2 m thick and consist of albite, quartz, microcline, muscovite, lepidolite and spessartine. Cassiterite is present throughout. Ellis (1950) stated that alluvium and eluvium to the east of the primary deposits contains 7 750 m^3 of material with 1.8 kg/m^3 of concentrate (SnO_2, 13.5 per cent). Blockley (1980) comments that these deposits are now regarded as worked out.

Small tonnages of tin concentrate have been obtained from Pilgangoora, Pinga, Pastoral Creek, Strelley, Daylight Creek (Bonney Downs), Upper Five Mile Creek and Mount Hall. All these deposits are described by Blockley (1980).

TUNGSTEN

Wolframite has been mined by prospectors in the Pilbara Block from pegmatites and quartz veins associated with some of the post-tectonic (2.6-2.7 m.y. old) granitic intrusions. Tin deposits associated with the batholiths are generally devoid of wolframite. Scheelite is rare in the Pilbara Block but has been recorded associated with gold at the Ard Patrick (Mosquito Creek centre) and Stray Shot mines (Marble Bar centre) and in silicic pegmatites in the country rock south of the Cookes Creek Granite. Production is summarized in Table 16.

Late-stage differentiated dykes intrude both the Cookes Creek Granite and adjacent country rock (chiefly metabasalt of the Salgash Subgroup). Most of the production recorded in Table 16 was obtained during 1951 and 1952 from pegmatite within the granite. The largest workings are in a 0.3 m wide quartz-pegmatite vein which is 400 m east of Cookes Creek, close to the southwestern margin of the pluton. The vein, which strikes west-northwest, has been worked to a depth of 10 m, and along strike for a distance of about 200 m. Wolframite is the principal ore mineral, but scheelite, fluorite and muscovite are accessories. A similar vein has been worked on the southern bank of the Nullagine River about 1 km west of Cookes Creek, but production figures are not available.

Outside the Cookes Creek granite small amounts of scheelite and wolframite have been mined from a 1 m wide quartz-rich pegmatite which intrudes mafic schist 2 km south-west of the principal mine. The closest granite occurs in a small stock about 50 m to the east of the vein, which is on, or very close to, a northwest-striking dextral fault through the greenstones. Apart from the ore minerals, fluorite, muscovite, and actinolite also occur in the vein.

TABLE 16. TOTAL PRODUCTION OF SCHEELITE AND WOLFRAMITE TO 31 DECEMBER 1977

Centre	*Scheelite concentrate (kg)*	*Wolframite concentrate (kg)*	*Contained WO_3 (kg)*
Cookes Creek	1 713	24 921	17 583.2
Friendly Creek		620	349.1
Mosquito Creek (Ard Patrick)	190		137.9
Shark (Burrows Well)		621	412.9
Talga Talga		162	95.2
TOTAL	1 903	26 324	18 578.3

10891—16

In 1957, 3.05 t of scheelite was mined from the Ard Patrick gold mine at the Mosquito Creek centre. Simpson (1952, p. 531) had previously drawn attention to the presence of the mineral at this locality, commenting that the scheelite occurred in bunches, closely associated with gold in a quartz vein 0.15-0.70 m wide. The quartz vein intrudes pelitic and psammopelitic schist of the Mosquito Creek Formation, the closest granite outcrops occur 6 km to the south and 6 km to the northeast.

The Burrows Well wolframite deposit is 4 km southeast of Split Rock homestead (abandoned), about 2 km west of the Cooglegong Adamellite's eastern margin. Wolframite is concentrated on the eastern side of a northerly trending quartz vein, but the deposit was small and appears to have been worked out.

A deposit of malachite and wolframite, first described by Maitland (1919, p. 3), has been mined at Black Gin Point (Friendly Creek centre). The mineralization is restricted to a quartz vein which intrudes metabasalt. Simpson (1952, p. 530) referred to scheelite at this locality. Scheelite occurs as a minor constituent of the alluvial cassiterite deposits at Friendly Creek, and has been reported in quartz veins and mica schist on Kingston's scheelite lease and ML 86 at Wodgina (Baxter, 1978).

The source of the Talga Talga wolframite production is unknown, but scheelite has been recorded (Marston, 1979) at Coppin Gap (13 km north of Talga Talga homestead). In 1978, 650 kg of wolframite-gold concentrate was obtained from the True Blue mine at Bamboo Creek mining centre.

Various occurrences of wolframite and scheelite which have not yielded production are recorded by Simpson (1951, 1952).

URANIUM

Radioactive minerals were first recorded at Wodgina (Simpson, 1912), but were found to be present in small concentrations only. No uranium deposits approaching economic grade have yet been discovered in the Pilbara Block, but the Lower Proterozoic Hardey Sandstone is known to be uraniferous at several localities. Robertson (1974, p. 506) commented that certain conglomerates within the formation are weakly radioactive in the range of 0.05-0.1 kg of U_3O_8 per tonne. One intersection from an unspecified locality was said to have yielded 0.39 kg of U_3O_8 per tonne over 1.5 m. In this case, uranium is associated with thucholite pellets; associated heavy minerals are pyrite, monazite, zircon, and anatase. Robertson considers that during the deposition of the Hardey Sandstone the Earth's atmosphere was anoxygenic, and syngenetic uraninite from pegmatite and gneiss was deposited in placers. Deposition from ground water or hydrothermal solutions is discounted because the uraninite has a high content of thorium and rare earths (unlike pitchblende), because the deposits are not related to faults or veins, and because clasts of radioactive conglomerate are found in otherwise non-radioactive conglomerate immediately overlying the mineralized horizons.

Three localities have been shown to contain anomalous concentrations of uranium: Bonnie Creek, Warralong Creek, and Croydon.

BONNIE CREEK

About 20 km west of Nullagine, Cominco Exploration Pty Ltd and Esso Australia Limited have reported conglomerate containing up to 360 ppm uranium in drill core and 1 223 uranium from surface samples. Background uranium contents generally range between 5 and 30 ppm. The Hardey Sandstone (which occupies an early Proterozoic depositional basin), is about 1 000 m thick in this area, and the conglomerate units can be traced for over 20 km along strike. Highest uranium contents are encountered in lenticular units of quartz pebble conglomerate that have an abnormally ferruginous matrix. On the surface, this ferruginous material is limonite, but at depth the conglomerate contains pyrite in the form of poorly rounded detrital grains and larger irregular masses within the matrix. The uraniferous conglomerate units at Bonnie Creek differ from the auriferous conglomerate at Nullagine in being more mature, better sorted and finer grained.

Most of the pebbles are composed of vein quartz whereas the conglomerate at Nullagine contains a large proportion of rock fragments.

The uraniferous horizons are sufficiently persistent to be correlated between drill holes, but under present conditions grade is far too low to permit mining.

WARRALONG CREEK

About 5 km south-southeast of Shady Camp Well a 1-2 m thick conglomerate within the Hardey Sandstone contains traces of gummite. A costean, where the road between Marble Bar and North Pole takes a sharp right-angle turn, has exposed conglomerate assaying 73 ppm uranium. Exploration in other parts of the area has not yet revealed any deposits approaching economic grade.

CROYDON

Uraniferous conglomerate has been discovered in the Hardey Sandstone 30 km south-southwest of Croydon homestead. A quartz pebble conglomerate in the centre of the formation assayed 427 ppm uranium over 2.9 m. Rock containing up to 300 ppm uranium exists along strike, but present indications are that the mineralization is irregular.

Exploratory work referred to above has established that the Hardey Sandstone is weakly uraniferous over a large part of the Pilbara Block. Many areas containing the formation appear not to have been examined for uranium mineralization, and an economic deposit may exist. The Witwatersrand placer deposits of South Africa exploit gold ore with an average content of 300 ppm uranium (Park and MacDiarmid, 1964), but climate, geographic position and the absence of a pre-existing mine infrastructure would probably require Pilbara ore to be considerably richer.

VANADIUM

Titaniferous magnetite has been known from Andover in the Pilbara Block since 1938, but it was not until the early 1960s that the vanadium content was determined. During regional exploration at this time, new deposits were found at Balla Balla, about 11 km north of Whim Creek Mine. The following descriptions are taken from Baxter (1978).

The three main deposits at Balla Balla are located in a saussuritized meta-gabbro sequence in which there is variation from leuco-gabbro to anorthosite. The sequence has a general strike of 080-100° and dips gently north at 25-30°. Faults in the vicinity of the deposit trend 020° and 140°; both sets of faults dip steeply east.

The westernmost hill in the main deposit has anorthositic gabbro and medium- to coarse-grained gabbro exposed on the southern side. The oxide bands are generally less than 0.5 m thick, but there are up to 12 bands across the hill separated by thin belts of chloritic rocks. The central hill contains a thin magnetite-banded zone bounded to the north by a chalcedony capping and to the south by gabbro. The eastern hill is composed of epidotized gabbro and anorthosite, but was apparently intruded by dolerite dykes as there are large areas of fine-grained dolerite scree on the hillslope. Two shafts, one 7.8 m deep and the other 10.4 m deep, have been sunk on the magnetite band. The magnetite bands are between 0.1 m and 0.5 m thick, and separated by 10-100 mm of chloritic rock.

The deposits were first examined by Mangore (Australia) Pty Ltd in 1961 and 1962. They estimated the ore reserves to be 1 938 kt averaging 0.75 per cent V_2O_5.

The Andover deposits, situated about 10 km west of Woodbrook (Andover) homestead and 2.5 km east-northeast of Black Hill Well, contain 17 lenses of titaniferous magnetite. They were first reported by Finucane and Telford (1939c) and were reviewed by Connolly in 1959. The host rock is a saussuritized metagabbro which contains both cumulus and intercumulus magnetite. The general strike of the foliation is 080° dipping north between 50° and 65°. The ore-bearing gabbro has been intruded by a younger, fine- to medium-grained gabbro, which contains no magnetite, and the whole succession is intruded by aplite veins.

The magnetite lenses are discontinuous and generally less than 200 m long and 2-5 m wide. They commonly contain a feldspar matrix, and, in some bands, ilmenite has been replaced by sphene. Disseminated pyrite occurs in some parts of the gabbro. The tonnages available for individual lenses are low, and the distribution of lenses makes the deposits of marginal economic interest.

Vanadinite occurs at Braeside, Talga Talga, and Western Shaw. The vanadium mineral was first discovered 11 km southeast of Braeside homestead in 1913 (Simpson, 1952, p. 685), where it is associated with considerable quantities of pyromorphite. An analysis of the mixed ore gave 54.74 per cent lead and 7.12 per cent V_2O_5. Other samples of lead and copper ore contained 16.9 per cent V_2O_5. About 10 km northwest of Koongaling Hill, a narrow siliceous vein containing lead and copper ores has been worked, but little production was obtained. One hole, 2.5 m deep, exposes a 0.4 m vein of galena. An assay of the ore recorded 16.0 per cent V_2O_5. Finucane (1938e) considered that the vanadium ores at Braeside are too scarce to be worked economically.

At Talga Talga and Western Shaw, vanadinite has been noted in concentrates from gold ore (Simpson, 1952, p. 688).

ZINC

Zinc production is recorded at the Braeside and Lennon Find centres, which are described elsewhere in the bulletin, and in more detail by Finucane (1938e), Low (1963), Blockley (1971b), and Marston (1979). About 26 t of zinc was obtained from lead ore at Braeside and 2.25 t from copper ore at Lennon Find. At Marble Bar the 'Big Stubby' prospect contains indicated reserves of between 0.1 and 0.2 Mt of ore with an average grade of 13.8 per cent zinc. The Mons Cupri ore contains 6.5-16.2 per cent zinc. Exploratory drilling for barite at North Pole resulted in the discovery of associated zinc mineralization, and, in 1972, Mogul Mining N.L. announced a 7.6 m intersection containing 7.7 per cent copper, 2.7 per cent lead, 7 g/t silver and 5.7 per cent zinc at Coondamar Creek. This depôsit occurs along a north striking fault through the Mosquito Creek Formation.

Zinc mineralization appears to be concentrated in sedimentary rocks at three stratigraphic levels within the Pilbara Supergroup; the top of the Duffer Formation, the Mosquito Creek Formation and the Mons Cupri Volcanics.

NON-METALLIC AND INDUSTRIAL MINERALS

ASBESTOS (CHRYSOTILE)

All the chrysotile deposits of the Pilbara (Table 17) occur in serpentinized peridotite. The two most important centres, Lionel and Nunyerry, merit brief descriptions.

TABLE 17. TOTAL PRODUCTION OF ASBESTOS TO 31 DECEMBER 1977

Centre	*Asbestos (t)*
Dead Bullock Well	34.36
Lalla Rookh	2.03
Lionel	4014.82
Nunyerry	6313.60
Roebourne	4.55
Sherlock	829.19
Soanesville	244.78
District generally	9.90
TOTAL	11453.23

LIONEL

Several chrysotile deposits have been mined at the Lionel centre, 26 km north of Nullagine. The workings are based on sills of serpentinized peridotite which intrude Archaean basalt, dolerite, and metasediments. The basaltic rocks belong to the Salgash Subgroup, and the metasediments to the Gorge Creek Group. About 3 kt of fibre have been extracted from Hancock's mine and about 1 kt from Stubbs' mine. Veinlets of fibre are 3-100 mm wide but average about 10 mm. In the main ore bodies, chrysotile makes up about 20-30 per cent of the rock. Further details are provided by Simpson (1922), Wilson (1922), Finucane, Sullivan and Telford (1939) and Blockley (1976).

NUNYERRY

The Nunyerry chrysotile mine is situated 110 km southeast of Roebourne. Serpentinite, felsic lava and ferruginous chert are intruded by an Archaean granitic batholith to the south and unconformably overlain by the Fortescue Group on all other sides. The Serpentinite is 750 m long and 75 m wide. Three principal chrysotile loads strike east-northeast and consist of lenticular zones of serpentinite containing numerous veinlets of cross-fibre. One of the lodes was mined over a length of 100 m to a depth of 60 m. Matheson (1951) and Finucane, Sullivan and Telford (1939) provided further descriptions of the deposits.

Other chrysotile deposits of the Pilbara Block are described in the various references cited above.

BARITE

Veins and beds of barite occur at North Pole, Marble Bar and Cooke Bluff Hill, but only the North Pole deposits have been mined.

NORTH POLE

The largest barite deposits known in Western Australia occur at North Pole, 40 km west of Marble Bar. In 1970, 528 t of barite were extracted; during 1976 and 1977 a further 19 216 t were mined.

Inferred reserves amount to several million tonnes.

The main deposits occur within the Towers Formation on the eastern and southeastern sides of the North Pole Dome. Hickman (1973) described the deposits as partly interbedded with chert and basalt, and partly occupying veins. Various features of the deposits led him to suggest that they originated as Archaean sediments but that tectonic deformation has resulted in mobilization of the barite into a local fracture system. Dunlop and others (1978) reached a similar conclusion, and present textural evidence that the barite formed by diagenetic replacement of an original evaporative gypsum-carbonate sequence. According to Dunlop (1976), chert units associated with the deposits show textures and fabrics similar to those of modern shallow water to supratidal carbonate successions, and Dunlop and others (1978) reported the presence of microfossils.

MARBLE BAR

The Big Stubby lead-zinc-silver prospect (described previously) contains up to 60 per cent barite in its gangue. between 0.10 and 0.15 Mt of barite and base metal sulphides could exist above 150 m depth (W. Brook, 1974). The Marble Bar deposits occur at approximately the same stratigraphic level as the North Pole deposits but are almost certainly volcanogenic.

COOKE BLUFF HILL

Recent mapping by the Geological Survey revealed the existence of large barite deposits near Cooke Bluff Hill, 100 km southeast of Port Hedland and 25 km to the north of North Pole. Hickman (1977b) put inferred resources at 0.5 Mt to a depth of 10 m. The barite occurs in veins and barite sandstone within Archaean sandstone, conglomerate, banded chert and felsic volcanogenic rocks. The barite sandstone appears to be a replacement deposit, barium being precipitated from surface water or hypogene solutions associated with volcanic activity. The veins of barite probably originated by deformation of the bedded deposits or by mobilization of barite associated with a nearby granitic intrusion.

CONSTRUCTION MATERIAL

The engineering properties of rocks, which include such features as strength, suitability for foundations, stability on slopes and in excavations, and suitability as construction materials, depend on physical and chemical composition, freshness and mode of occurrence. Granitic rocks are strong and stable when fresh, but in surface exposures are generally weakened and less stable due to weathering. Effects of the latter rarely extend to more than a metre in the Pilbara and more commonly are confined to joint planes.

Proterozoic basalt and dolerite tend to be internally more uniform and less deformed than their Archaean counterparts and consequently present fewer engineering problems. Rocks such as schist and bedded sedimentary rocks are susceptible to failure along foliation planes, and plans for excavations or heavy constructions must take this into account. Limestone and sandstone may be highly jointed and are thus susceptible to failure in several directions.

There is an abundance of material suitable for road and rail ballast, housing foundation pads, aggregate and road metal. Granite and basalt have been quarried along the railway lines and gravel colluvium and laterite have been used during construction of the main roads. Expansive clay (*Qe* on Plate 1A) should be avoided when foundation material is obtained or when building sites are selected. This type of clay expands during wet periods and contracts during droughts, placing considerable strains on any constructions resting on it.

The various beach and dune deposits are generally friable, and, when loose, may be unstable in excavations and on slopes. They are liable to erosion if cleared of vegetation and, except for older leached deposits, are of limited use in construction because of their high salt content.

DIAMOND

Nullagine was the scene of Western Australia's first diamond discovery in 1895 (Groom, 1896) and by 1973 at least 70 diamonds had been picked up. Most of the gems appear to have been obtained from Cainozoic sediments about 1 km northwest of the town. Sofoulis (1958b) and Noldart and Wyatt (1962) stated that the diamonds have been weathered from auriferous conglomerate of the Hardey Sandstone, but Carter (1974) commented that recent exploration work indicates that the source is Tertiary sandstone. Diamonds are formed in kimberlite pipes, but no such intrusion has been identified in the Pilbara Block.

EMERALD

In 1954, 8.68 carats (cut) of emerald were obtained from pegmatite intruding biotite schist and migmatite at McPhee's Hill, 8 km north of Lynas Find. Emerald also occurs in lenses of pegmatite within biotite-chlorite schist 6 km southwest of Calvert's White Quartz Hill, but no production has been officially recorded. In 1931, a prospector found a few crystals of emerald in the Wodgina district, about 3 km northwest of the Tantalite Lode. Simpson (1948, p. 197) described them as prisms embedded in feldspar, and reaching 10 mm in length and 5 mm in width. The stones were considered to be too turbid and flawed to be worth cutting. Emerald of variable quality has been noted in pegmatite which intrudes ultramafic schist at Pilgangoora. The principal occurrence is located about 4 km north-northeast of Coffin Bore; no production is recorded.

FLUORITE

Fluorite deposits occur at Meentheena, Cookes Creek, and Ngarrin Creek. The Meentheena deposits have been mined, and although about 8 kt of fluorite was extracted from the workings, no production has been officially recorded.

MEENTHEENA

The fluorite at Meentheena (220 km east-southeast of Port Hedland) occurs in quartz veins up to 5 m wide and, in one case, 1 600 m long. In the richer deposits, white to purple fluorite comprises over 50 per cent of the ore. The veins penetrate agglomerate, basalt and andesite of the Mount Roe Basalt, and occupy a conjugate fracture system within the core of an open northwest trending anticline (Hickman, 1973). The inferred resources of the deposits are 13 kt of fluorite (50 per cent CaF_2) per vertical metre. The main impurities are quartz and altered country rock.

COOKES CREEK

The Cookes Creek Granite contains veins of fluorite and quartz, but none of the deposits appear to be sufficiently large to justify mining. The granite is a post-tectonic intrusion dated by de Laeter and others (1977) at 2 600 m.y., and the quartz-fluorite veins are interpreted as late-stage emanations.

NGARRIN CREEK

About 27 km south-southwest of Callawa homestead, a stock of fluorite porphyry intrudes the Warrawagine Batholith. The mineral occurs in microscopic veins and in vugs (0.2-50 mm), but the overall fluorite content of the rock is only about 1.5 per cent (Hickman, 1976).

GADOLINITE

In 1913, 1.02 t of gadolinite was mined from pegmatite said to be 6.4 km east of the site of the former Cooglegong Hotel (Simpson, 1951, p. 294) and 0.8 km west of the Black Range (Miles and others, 1945, p. 130). Its approximate position is Latitude 21° 35′S, Longitude 119° 28′E. Simpson (1951) stated that 1.02 t of gadolinite was also produced from this locality in 1920 (the Mines Department Annual Report for 1920 noted production of 1.02 tonnes under 'State Generally'). Simpson found gadolinite in two pegmatite veins 3 km to the west of the mined deposit, and the mineral has also been recorded 16 km southwest of Abydos and in pegmatite at the Fibre Queen, Dead Bullock Well (Simpson, 1951, p. 293).

LIMESTONE AND LIMESAND

Potential sources of calcium carbonate in the Pilbara Block area are the Meentheena Carbonate Member, Carawine Dolomite, Oakover Formation (where non-silicified), Bossut Formation, and Quaternary lime sand. Baxter (1972) found that the Carawine Dolomite ('Wittenoom Dolomite'), while principally true dolomite, does contain some units of limestone. One sample from the Hamersley Range assayed 88.2 per cent CaO, 1.64 per cent SiO_2, 3.1 per cent MgO, 1.90 per cent Fe_2O_3, and 0.78 per cent Al_2O_3. Baxter recommended prospecting for limestone using a test solution made up of 2 per cent alizirin and 2 per cent hydrochloric acid, which stains calcite red but does not affect dolomite.

Samples of calcrete from near Roy Hill homestead (just south of the Pilbara Block area) included limestone but were siliceous. Prospecting might reveal purer material.

The Bossut Formation is a siliceous limestone, $CaCO_3$ contents ranging from 43.6-87.5 per cent, and SiO_2 from 43.2-5.68 per cent (Baxter, 1972). Limestone suitable for cement manufacture, metallurgy, dimension stone, and road construction occurs on Legendre Island, Hauy Island, Collier Rocks, Cohen Island, Keast Island, Delambre Island, and along the coast near Port Hedland. Mining in the Dampier Archipelago during 1974 and 1975 yielded over 250 kt of limestone. Reserves are considered to be very large, but regional variations in quality have not been fully assessed. Mining in certain areas would encounter environmental objections.

Limesand, in the form of shell beds, has been quarried at Hearson Cove where $CaCO_3$ content is about 80 per cent, silica being the chief impurity. Between 1974 and 1977, 93 704 t of limesand was obtained at Cleaverville, but the quality of this material is not recorded.

MICA

Only muscovite and phlogopite are commercially important as sheet mica, which is used in the electrical industry as an insulator. The minimum surface area of useful sheets is about 650 mm^2 (Berkman, 1976, p. 81). Virtually all the pegmatites contain muscovite, but large sheets are only common at a few localities; examples are Pippingarra, Pilgangoora, Turkey Camp Well, Numbana, and Wodgina. Masses of the mineral locally measure several metres across and up to 0.2 m thick, but the sheets are commonly fractured.

ORNAMENTAL STONE

TIGER-EYE

Tiger-eye opal set in red, brown, and black jaspilite has been mined in the Ord Range. When polished, the most silicified and consequently the hardest specimens make attractive small ornaments. The golden brown bands of tiger-eye measure up to 10 mm wide and hundreds of millimetres long, although most are lenticular. The bands are thickest and most numerous close to the axial regions of minor folds. Typical seams (i.e. groups of bands clustered closely enough to be extracted as a unit) range from 0.1-2.0 m in stratigraphic thickness (Blockley, 1976).

The tiger-eye was formed by oxidation and silification of a pre-existing amphibole asbestos, probably crocidolite. Growth of crocidolite fibre took place along planes of sedimentary layering in the banded iron-formation. Its relationship to the fold structures suggests preferential development at points where tensional forces normal to the layering were at a maximum. The existence of crocidolite indicates the local presence of sodium during diagenesis (cf. Trendall and Blockley, 1970).

GREEN GEM MATERIAL

Mr S. H. Stubbs of the Comet mine, Marble Bar has recently marketed ornaments and jewellery made of a polished green stone referred to as "Pilbara Jade" (also known as "Marble Bar Jade"). Hudson (1974) stated that X-ray diffraction studies have established that the stone is not true jade (jadeite or nephrite), but essentially a combination of chlorite (clinochlore), aluminous serpentine and chrysotile. Nevertheless, harder specimens of the stone are extremely attractive when polished.

The 'Pilbara Jade' is mined at Lionel, where it occurs as lenses in serpentinite. Like the nearby chrysotile deposits, the rock probably formed by hydrothermal alteration of peridotite, but sufficient aluminium must have accumulated in order to form chlorite rather than serpentine.

Chlorite-serpentine rocks, chrysoprase and green chert suitable for making ornaments occur in several areas of the Pilbara Block. Chlorite-serpentine rocks are associated with peridotite bodies at Soanesville and Lionel (Simpson, 1948) and an opaline replacement of peridotite occurs at Pear Creek. Bright green chert 3 km north of Edna Well has been excavated as a source of ornamental stone. Microscopic examination suggests that the colouration results from a chromium impurity. Hudson (1974) referred to a chrysoprase mine situated about 500 m northwest of the Carlow Castle mine, 10 km southwest of Roebourne. The rock is cherty, bright velvet green, and figured with veins of black and white silica. Green chert also occurs 2 km south of Karratha and at localities cited in Chapter 2.

OTHER GEM MATERIAL

Grossular garnet, zoisite and rhodonite (red) have been reported at Roebourne, but precise localities are not recorded. It is possible that some of these semi-precious stones came from the Mount Hall area, 4 km east-southeast of the town. Tourmaline is widespread in the Archaean pegmatite veins of the Pilbara Block; most of the material is black and opaque but blue tourmaline is found at Wodgina. Agate occurs in vugs and amygdales within the Maddina Basalt throughout the Chichester Range. Veins of banded chalcedony up to 0.3 m thick occur in Archaean felsic volcanics between Copper Hills and Budjan Creek. Amethyst has been reported at a few localities, but the quality of the stone is generally poor. Topaz collected from a dump at Mount Francisco is white and opaque, but translucent varieties could be present.

SALT

Salt is obtained by evaporation of seawater at Port Hedland and Dampier. After initial concentration in lagoons the brine is pumped into pens and allowed to evaporate to dryness. In the first year of production (1969) Port Hedland produced about 0.3 Mt of salt (Lloyd, 1970, p. 25) and a future target was stated to be 1 Mt per annum. At Dampier, construction of evaporation ponds commenced in 1969, and by March, 1970, seawater had been allowed to flood approximately 4 050 ha, an area theoretically capable of producing about 0.8 Mt of salt per annum. In 1972, Dampier Salt Limited exported 348 625 t, and in the following year, production had risen to 993 658 t. By 1974, production exceeded 1.3 Mt, and operations have since continued to expand.

WATER

A detailed description of the hydrogeology of the Pilbara Block is beyond the scope of this bulletin, and only a brief outline of the area's water resources is presented here. Additional information is presented by Balleau (1973) and Davidson (1975); details can be obtained from the Hydrogeology Division of the Geological Survey.

Quaternary and Tertiary unconsolidated rock is the most widely exploited aquifer in the Pilbara Block; it supplies water to bores and wells for pastoral stations, mines and townships. A large volume of good quality water is stored in river bed sands after floods and Balleau (1973) estimated that such river bed reservoirs contain between 25 x 10^3 m^3 and 300 x 10^3 m^3 per kilometre. Intermittent river-flows may put ten times more water into the river alluvium than the groundwater outflow can discharge (Balleau, 1973), and much water is lost by evaporation from pools and transpiration through vegetation.

In pastoral country, wells equipped with windpumps are spaced fairly evenly at about 6-8 km intervals. Examination of these wells reveals that the level of the water table ranges from 1-30 m below surface, and that salinity varies from 200 ppm to 10 000 ppm dissolved salts. In general, the water table is closest to the surface, and the salinity is lowest (normally 1 500 ppm or less) close to creeks and rivers. Wells more than a few kilometres from the water courses or upstream from rock bars (e.g. dykes or quartz veins crossing the creeks) tend to exhibit salinity levels in the range of 1 000 to 5 000 ppm.

Springs, rockholes, and permanent or semipermanent pools containing quite good water are located in areas of dissected plateau, especially where deep gorges cut through the Proterozoic succession. Hardrock aquifers, where groundwater storage relies on fractures and joints, could partly satisfy the increasing demand for water in the area. Rocks worth investigating include the calcrete deposits of the Oakover Valley (calcrete at Millstream in the Fortescue valley is an important source of groundwater), the Hardey Sandstone in the Meentheena Basin and in the Oakover Syncline at Miningarra Creek, the Carawine Dolomite (especially where it occurs at depth below the water table) fractured dolerite dykes and quartz veins (especially close to drainage channels and where topographically low), and deeply weathered granite. Areas of deeply weathered granite may be encountered along ancient drainage courses, beneath Mesozoic and Cainozoic deposits or immediately below the Archaean-Proterozoic unconformity.

APPENDIX H EXPLANATION OF PLATE 2

Location of sections: A, Devil Creek 40 km west-southwest of Dampier; B, Whundo (base of section) to Mount Roe; C, Ruth Well-Nickol Bay area to Wickham; D, Friendly Creek to Egina; E, Pilgangoora; F, lower part southwards from Strelley Pool, upper part 15 km southwest of Lalla Rookh; G, North Pole to Panorama Ridge; H, Shark; I, Talga Talga to Marble Bar; J, Bamboo Creek; K. Camel Creek; L, lower part Sandy Creek, upper part Spinaway Creek; M, Stony Creek; N, McPhee Creek to Twenty Mile Sandy Creek; O, Elsie to Eastern Creek; P, Croydon to Whim Creek; Q, Goldsworthy; R, Shay Gap; S, Gorge Creek; T, Soanesville; U, Coongan; V, Kelly; W, Copper Hills; X, Sandy Creek to Charteris Creek.

Notes: Columns A to O provide a west-east section across the Pilbara Block. Some of the successions are generalized.

APPENDIX I—GAZETTEER OF LOCALITIES REFERRED TO IN TEXT

Mines are not listed except where well removed from centre localities.

	Latitude (S)	Longitude (E)
Abydos homestead	21°25′	118°55′
Abydos mine	21°36′	118°55′
Ailsa Well	21°26′	118°49′
Andover homestead	20°55′	117°07′
Andover mine	20°53′	117°07′
Ant Hill	22°06′	120°36′
Apex mine	21°16′	119°48′
Balfour Downs homestead	22°48′	120°52′
Balla Balla	20°40′	117°47′
Balla Balla Landing	20°40′	117°47′
Balmoral homestead	21°09′	116°07′
Bamboo Creek mining centre	20°55′	120°13′
Bamboo Springs homestead	22°03′	119°38′
Baramine homestead	20°52′	120°58′
Barton Battery	21°52′	120°18′
Benmore Well	21°04′	117°39′
Big Stubby mine	21°13′	119°45′
Billjim mine	21°49′	120°23′
Binbianna Rock Hole	21°57′	121°22′
Bindoo Well	21°14′	120°17′
Black Gin Point	21°12′	118°22′
Black Hill Well	21°22′	118°57′
Black Range	21°35′	119°28′
Blue Bar mine	21°24′	119°42′
Blue Spec mine	21°49′	120°16′
Bonney Downs	22°11′	119°56′
Bonnie Creek	21°58′	119°58′
Bonnie Pool	21°59′	119°59′
Boodalyerrie Creek	21°24′	120°52′
Boodalyerrie mining centre	21°35′	120°47′
Boodarrie	20°25′	118°23′
Bookabunna Well	21°17′	120°35′
Bowls Gorge	21°03′	119°41′
Box Well	20°55′	119°58′
Braeside lead field	21°07′	121°04′
Budjan Creek	21°50′	119°52′
Bullen Hill	20°34′	118°35′
Bulletin mine	20°56′	120°14′
Bullock Hide Well	20°54′	116°48′
Bunmardie Creek	21°10′	120°47′
Burrows Well	21°29′	119°37′
Cajuput Creek	21°57′	120°07′
Callawa homestead	20°38′	120°30′

	Latitude (S)	Longitude (E)
Calverts White Quartz Hill	21°32′	119°20′
Camel Creek	21°19′	119°45′
Canning Tin	21°41′	119°19′
Cape Lambert	20°36′	117°11′
Cape Preston	20°50′	116°12′
Carawine Gorge and Pool	21°29′	121°02′
Carbana Pool	21°33′	119°55′
Carlow Castle mine	20°49′	117°04′
Charteris Creek	21°28′	120°09′
Cheearra	21°24′	118°14′
Chichester Range	21°10′	119°00′
Chinaman Creek	21°10′	119°41′
Chinaman Pool	21°11′	119°42′
Chirratta homestead	21°02′	116°49′
Cleaverville	20°39′	117°00′
Coffin Bore	21°06′	118°53′
Cohen Island	20°23′	116°48′
Collier Rocks	20°24′	116°52′
Comet mine	21°14′	119°44′
Condon	20°00′	119°21′
Cooglegong Creek	21°35′	119°25′
Cooke Bluff Hill	20°57′	119°22′
Cookes Creek mine and mining centre	21°39′	120°27′
Coolbanacoula Pool	21°59′	119°47′
Coomba Creek	21°58′	119°34′
Coonabunna Creek	21°06′	120°37′
Coondamar Creek	21°56′	120°39′
Coondina mine	21°53′	119°23′
Coondina Pool	21°51′	119°23′
Coongan Belt mining centre	21°47′	119°40′
Coongan River	20°45′	119°40′
Coorong Creek	21°37′	118°54′
Cooya Pooya homestead	21°02′	117°08′
Copenhagen mine	21°18′	119°49′
Copper Creek	21°26′	120°17′
Copper Gorge mining centre	21°37′	120°20′
Copper Hills mining centre	21°39′	119°58′
Coppin Gap	20°53′	120°07′
Corboy mining centre	21°44′	119°39′
Corunna Downs homestead	21°28′	119°50′
Cossack	20°39′	117°10′
Croydon	21°08′	117°51′
Cundaline Gap	20°35′	120°12′
Cunmagunna Hill	21°45′	118°53′
Dalton Creek	21°25′	119°17′
Dalton mining centre	21°28′	119°16′
Dampier	20°40′	116°41′
Dampier Archipelago	20°30′	116°35′
Davis River	21°53′	121°00′
Daylight Creek	22°06′	120°03′
Dead Bullock Well	21°37′	119°06′

	Latitude (S)	Longitude (E)
Delambre Island	20°27′	117°04′
Devil Creek	21°00′	116°22′
Dewhurst Well	21°52′	120°08′
Dixon Island	20°37′	117°04′
Doherty mining centre	21°34′	120°15′
Doolena Gap	20°56′	119°47′
Doolena mine	20°53′	119°43′
Dromedary Hill	21°57′	120°08′
Duffer Creek	21°08′	119°46′
Eastern Creek mining centre	21°42′	120°37′
Eastern Creek Government Well	21°42′	120°37′
Eel Creek	20°35′	120°20′
Eera Baranna Pool	21°58′	118°35′
Egina mining centre	21°06′	118°15′
Eginbah	20°52′	119°47′
Eleys mining centre	21°42′	119°28′
Elsie mining centre	21°36′	120°35′
Elsie Well	21°36′	120°35′
Emu Creek	21°38′	119°57′
Emu Creek East mine	21°38′	119°59′
Enderby Island	20°37′	116°30′
Eramurra Creek	21°00′	116°15′
Eramurra Pool	21°05′	116°15′
Euro mine	21°18′	119°48′
Farrel Well	20°49′	119°32′
Fibre Queen mine	21°37′	119°08′
Five Mile Creek (Hillside)	21°40′	119°23′
Five Mile Creek (Nullagine)	21°53′	120°11′
Flat Rock mine	21°41′	117°53′
Francisco Well	21°23′	118°33′
Fred Well	20°59′	118°44′
Friendly Creek mining centre	21°14′	118°20′
Gallops Well	21°30′	120°06′
Garden Creek	21°53′	119°16′
Garden Pool	21°55′	120°06′
Geeman Well	20°57′	117°47′
Glen Ellen Pool	21°47′	119°54′
Glen Herring	21°20′	119°40′
Glen Herring Creek	21°23′	119°38′
Glen Roebourne	20°48′	117°05′
Goldsworthy	20°22′	119°31′
Good Luck Well	20°56′	117°41′
Gorge Creek	20°51′	119°31′
Gorge Range	20°54′	119°35′
Granite Hills Well	21°50′	120°29′
Granite Well	20°53′	120°37′
Grants Hill	21°53′	120°06′
Green Hole	20°56′	120°18′
Gregory Gorge	21°34′	116°55′
Gregory Range	21°15′	121°10′

	Latitude (S)	Longitude (E)
Hamersley Range	22°30′	118°30′
Harding River	20°50′	117°16′
Hartigan Creek	21°32′	119°32′
Hauy Island	20°26′	116°57′
Hay Creek	21°50′	120°45′
Haystack Well	22°11′	120°03′
Hearson Cove	20°38′	116°48′
Helen Well	20°52′	120°21′
Hillside homestead	21°43′	119°24′
Hillside mine (Weerianna)	20°46′	117°07′
Honeyeater Creek	21°14′	119°16′
Hong Kong mining centre	21°11′	118°17′
Hooley homestead	21°52′	118°13′
Indee homestead	20°47′	118°36′
Isabella Range	20°57′	121°06′
Jimmawurrada Creek	21°50′	116°20′
Jim Well	21°55′	119°52′
Just-in-time mine	21°15′	119°43′
Kangan homestead	21°06′	118°31′
Kangan Pool	21°06′	118°26′
KAP 2	20°53′	116°25′
Karratha	20°44′	116°51′
Keast Island	20°23′	116°50′
Kelly mining centre	21°47′	119°52′
Kimberley Gap	20°38′	120°19′
Kitty Gap	20°53′	120°05′
Koongalling Hill	21°04′	121°07′
Kunagunarrina Pool	21°15′	118°51′
Lalla Rookh homestead	20°53′	119°08′
Lalla Rookh mining centre	21°03′	119°17′
Legendre Island	20°23′	116°53′
Leilera Creek	21°19′	119°13′
Lennon Find mining centre	21°22′	120°14′
Lionel mining centre	21°40′	120°06′
Little Shaw Well	21°04′	119°27′
Little Sherlock River	20°55′	117°30′
Lockyer Gap	20°59′	117°05′
Lookout Rocks	21°57′	121°24′
Louden Creek	20°54′	117°48′
Lower Nickol mining centre	20°45′	116°57′
Lynas Find mine	21°00′	118°56′
Mallina homestead	20°54′	118°02′
Marble Bar	21°10′	119°45′
Marble Bar Pool	21°11′	119°43′
McLeods Reward	21°28′	119°15′
McPhee Creek	21°38′	120°12′
McPhee Hill	20°59′	118°56′
McPhee Reward mine	21°00′	119°49′

	Latitude (S)	Longitude (E)
Meentheena	21° 18′	120° 28′
Middle Creek mining centre	21° 52′	120° 18′
Mills Find mine	21° 17′	118° 37′
Millstream homestead	21° 35′	117° 04′
Miningarra Creek	20° 54′	120° 20′
Miralga Creek	20° 58′	119° 25′
Mondana Pool	21° 46′	119° 49′
Mons Cupri	20° 53′	117° 48′
Moolyella	21° 08′	119° 54′
Moorambinar Pool	21° 13′	117° 50′
Mosquito Creek mining centre	21° 50′	120° 30′
Mount Ada mine	21° 26′	119° 37′
Mountain Well	20° 57′	117° 40′
Mount Anketell	20° 40′	117° 05′
Mount Berghaus	20° 46′	118° 26′
Mount Cecilia	20° 48′	120° 59′
Mount Cooke mining centre	22° 08′	120° 38′
Mount Divide	22° 23′	120° 49′
Mount Edgar homestead	21° 19′	120° 04′
Mount Elsie	21° 36′	120° 35′
Mount Fisher	20° 54′	117° 28′
Mount Francisco	21° 22′	118° 33′
Mount Fraser	20° 56′	117° 33′
Mount Goldsworthy	20° 22′	119° 32′
Mount Gratwick	21° 41′	118° 37′
Mount Hall	20° 47′	117° 11′
Mount Herbert	21° 50′	117° 12′
Mount Ian	21° 14′	120° 46′
Mount Ian Well	21° 19′	120° 40′
Mount Langenbeck	21° 01′	118° 12′
Mount Leopold	20° 59′	116° 37′
Mount Negri	20° 48′	117° 51′
Mount Nicholas	22° 39′	120° 33′
Mount Oscar	20° 54′	117° 19′
Mount Princep	20° 52′	116° 48′
Mount Regal	20° 50′	116° 45′
Mount Roe	20° 55′	117° 06′
Mount Satirist	21° 08′	118° 05′
Mount Sholl	20° 55′	116° 54′
Mount Sydney	21° 24′	121° 12′
Mount Wohler	21° 19′	117° 39′
Mount York	21° 06′	118° 54′
Muccan homestead	20° 38′	120° 04′
Mulgandinnah Creek	21° 28′	119° 22′
Mumbillina mine	21° 36′	118° 20′
Mundermullancunder Pool	21° 26′	118° 40′
Mundine Well	21° 41′	119° 05′
Munni Munni Creek	21° 07′	116° 50′
Nardoopiquithanna Pool	21° 17′	118° 44′
Newman	23° 23′	119° 40′
Ngarrin Creek	20° 50′	120° 28′

	Latitude (S)	Longitude (E)
Nickol River	20°50′	116°56′
Nimerry Creek	20°57′	119°57′
Nimingarra homestead	20°31′	119°54′
Nobb Well	20°59′	120°11′
Normay mine	21°06′	119°24′
North Pole mining centre	21°06′	119°22′
North Shaw mining centre	21°20′	119°22′
North Shaw Well	21°19′	119°23′
North Star mine	21°01′	119°50′
Nullagine	21°53′	120°06′
Numbana mine	21°20′	118°38′
Nunyerry Gap	21°28′	117°54′
Nunyerry mine	21°33′	117°56′
Oakover River	21°10′	121°00′
Old Indee Well	20°42′	118°35′
Old Shaw Creek	21°40′	119°29′
Olsen Well	20°28′	119°52′
Ord Range	20°17′	119°08′
Paddy Market Creek	21°23′	119°15′
Paddy Market Gorge	21°23′	119°15′
Pannawonica	21°47′	116°22′
Panorama Ridge	21°16′	119°28′
Paraburdoo	21°14′	117°32′
Pastoral Creek	21°18′	118°47′
Paterson Range	21°50′	122°08′
Pearana Rock Hole	21°54′	121°14′
Pear Creek	20°52′	119°36′
Peawah Hill	20°38′	117°55′
Peawah mine	20°52′	118°08′
Pelican Pool	21°20′	120°22′
Phoenix mine	21°16′	119°47′
Pilbara mining centre	21°13′	118°17′
Pilbara Well	21°14′	118°18′
Pilga	21°29′	119°24′
Pilgangoora mining centre	21°03′	118°54′
Pincunah Water Hole	21°12′	118°49′
Pinga	21°31′	118°48′
Pippingarra mining centre	20°35′	118°46′
Point James	20°57′	116°11′
Police Creek	21°30′	120°23′
Poondano Rock Hole	20°27′	118°48′
Port Hedland	20°18′	118°35′
Portree	20°47′	118°20′
Prospectors Creek	21°10′	119°53′
Pyramid homestead	21°04′	117°26′
Pyramid Well	21°07′	119°48′
Radio Hill	20°59′	116°50′
Radleys (Upper Nickol)	20°53′	116°53′
Ragged Hills mine	21°18′	121°09′

	Latitude (S)	Longitude (E)
Red Rock Creek	20°36′	119°04′
Reedy Creek	21°39′	120°21′
Ripon Hills	21°13′	120°44′
Robe River	21°45′	116°35′
Roebourne	20°44′	117°08′
Round Hummock	21°17′	118°37′
Roy Hill homestead	22°37′	119°57′
Rushall mine	20°51′	117°50′
Ruth Well	20°45′	116°49′
Salgash mining centre	21°17′	119°48′
Samphire Marsh No. 1 Well	19°31′	121°11′
Sampson Creek	20°52′	119°53′
Sandy Creek	21°28′	120°04′
Shady Camp Well	21°10′	119°34′
Shark mining centre	21°26′	119°37′
Shaw Gorge	21°18′	119°19′
Shaw Patch	21°34′	119°23′
Shay Gap	20°30′	120°10′
Sherlock homestead	20°53′	117°38′
Sherlock Bay prospect	20°49′	117°32′
Sherlock River	20°50′	117°35′
Six Mile Creek	21°10′	119°08′
Skull Springs mining centre	21°52′	121°03′
Snell Well	20°52′	121°05′
Soanesville mining centre	21°32′	119°11′
Spear Hill	21°31′	119°24′
Spinaway Creek	21°35′	120°01′
Spinaway Well	21°37′	120°04′
Split Rock	21°32′	119°35′
Stannum mine	21°15′	118°38′
Station Peak mining centre	21°10′	118°10′
Stinking Pool	21°20′	119°01′
Strelley Gorge	21°07′	119°08′
Strelley homestead	20°26′	118°59′
Strelley mining centre	20°32′	119°01′
Strelley Pool	21°06′	119°08′
Sunday Hill	22°04′	120°33′
Sunrise Hill	20°27′	120°03′
Tabba Tabba homestead	20°50′	118°54′
Tabba Tabba mining centre	20°40′	118°55′
Talga Peak	20°54′	119°56′
Talga Talga mining centre	21°00′	119°50′
Talye Well	20°53′	118°37′
Tambina Creek	21°37′	119°13′
Tambourah Creek	21°42′	119°20′
Tambourah homestead	21°45′	119°10′
Tambourah mining centre	21°45′	119°11′
Teichmans mine	21°17′	118°12′
Tom Price	22°45′	117°47′
Tooncoonaragee Pool	21°38′	121°09′
Toweranna mining centre	20°58′	117°52′

	Latitude (S)	Longitude (E)
Towers mine	21°16′	119°48′
True Blue mine	20°55′	120°13′
Turkey Camp Well	20°35′	118°30′
Turner River	20°35′	118°30′
Twenty Mile Sandy Battery	21°51′	120°21′
Twenty Mile Sandy mining centre	21°51′	120°21′
Twenty Ounce Gully	21°11′	120°22′
Two Mile Creek	21°33′	119°25′
Two Sisters	21°29′	120°07′
Upper Carawine Gorge	21°33′	121°06′
Upper Five Mile Creek	22°02′	120°13′
Upper Nickol mining centre	20°53′	116°53′
Wallabirdee Ridge	21°30′	120°17′
Wallareenya	20°45′	118°49′
Waltha Woora Creek	21°33′	121°11′
Wandy Wandy Creek	21°29′	121°17′
Warambie homestead	20°57′	117°22′
Warralong Creek	21°00′	119°40′
Warrawagine	20°52′	120°41′
Warrawoona mining centre	21°20′	119°54′
Warrawoona Peak	21°20′	119°53′
Warrery Gap	21°35′	119°45′
Weerianna mining centre	20°46′	117°07′
Western Shaw mining centre	21°46′	119°12′
West Wodgina	21°10′	118°39′
Whim Creek mining centre	20°52′	117°50′
White Springs homestead	21°47′	118°49′
Whundo mine	21°06′	116°55′
Wickham	20°40′	117°08′
Windywindina Creek	21°57′	120°32′
Withnell Creek	21°40′	119°40′
Wittenoom	22°15′	118°20′
Wittenoom Gorge	22°20′	118°19′
Wodgina mining centre	21°11′	118°41′
Woodie Woodie mining centre	21°38′	121°14′
Woodstock homestead	21°37′	118°57′
Wyman Well mining centre	21°18′	119°48′
Yandeearra homestead	21°17′	118°24′
Yandicoogina mining centre	21°25′	120°11′
Yannery Hill mining centre	21°05′	116°56′
Yarrie homestead	20°40′	120°11′
Yilgalong Creek	21°30′	120°42′
13 Mile Quarry	20°32′	118°38′
40 Mile Quarry	20°55′	118°41′
70 Mile Quarry	21°23′	118°54′
127 Mile Quarry	21°57′	119°01′

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SUBJECT INDEX

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AUTHOR INDEX

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PILBARA BLOCK

GEOLOGICAL SURVEY OF WESTERN AUSTRALIA

BULLETIN 127 PLATES 1A AND 1B

STRATIGRAPHIC INTERPRETATION REFERENCE

PHANEROZOIC

- JK — Mesozoic rocks, includes CALLAWA FORMATION
- P — Permian rocks, includes PATERSON FORMATION

PROTEROZOIC

INTRUSIVE ROCKS

- Ꝑy — Granophyre
- Ꝑdc — COOYA POOYA DOLERITE
- Ꝑd — Dolerite
- Ꝑo — Gabbro
- Ꝑps — SPINAWAY PORPHYRY
- Ꝑpb — BAMBOO CREEK PORPHYRY
- Ꝑg — Hornblende adamellite

- ꝐG — MANGANESE GROUP

unconformity

- ꝐY — YENEENA GROUP
- Ꝑe — EEL CREEK FORMATION
- Ꝑe(i) — Iron-formation (clastic)
- Ꝑw — WALTHA WOORA FORMATION: shale and carbonate

unconformity

- Ꝑcb — PINJIAN CHERT BRECCIA

unconformity

Hamersley Group

- ꝐHw — WEELI WOLLI FORMATION: jaspilite and shale
- ꝐHb — BROCKMAN IRON FORMATION
- ꝐHs — MT McRAE SHALE & MT SYLVIA FORMATION
- ꝐHc — CARAWINE DOLOMITE – WITTENOOM DOLOMITE
- ꝐHm — MARRA MAMBA IRON FORMATION

Fortescue Group

- ꝐFj — JEERINAH FORMATION: shales, minor sandstone and chert
- ꝐFm — MADDINA BASALT
- ꝐFs — KURUNA SILTSTONE
- ꝐFp — PEARANA BASALT
- ꝐFn — NYMERINA BASALT
- ꝐFt — TUMBIANA FORMATION: carbonate and tuff (stromatolites)
- ꝐFk — KYLENA BASALT
- ꝐFk(s) — Sandstone and grit
- ꝐFh — HARDEY SANDSTONE
- ꝐFr — MT ROE BASALT
- ꝐFi — KOONGALING VOLCANICS: felsic

unconformity

ARCHAEAN

INTRUSIVE ROCKS

- Ap — Felsic porphyry
- Ad — Dolerite
- Ao — Gabbro
- Au — Ultramafic rock

- An — NEGRI VOLCANICS

unconformity

- Al — LOUDEN VOLCANICS

faulted contact at Whim Creek

Whim Creek Group

- ACr — RUSHALL SLATE
- ACm — MONS CUPRI VOLCANICS
- ACw — WARAMBIE BASALT

unconformity

Gorge Creek Group

- AGm — MOSQUITO CREEK FORMATION – MALLINA FORMATION
- AGl — LALLA ROOKH SANDSTONE
- AGh — HONEYEATER BASALT
- AGs — SOANESVILLE SUBGROUP
- AGi — CLEAVERVILLE FORMATION: BIF, ferruginous chert
- AGb — CHARTERIS BASALT
- AGc — CORBOY FORMATION: sediments

Warrawoona Group

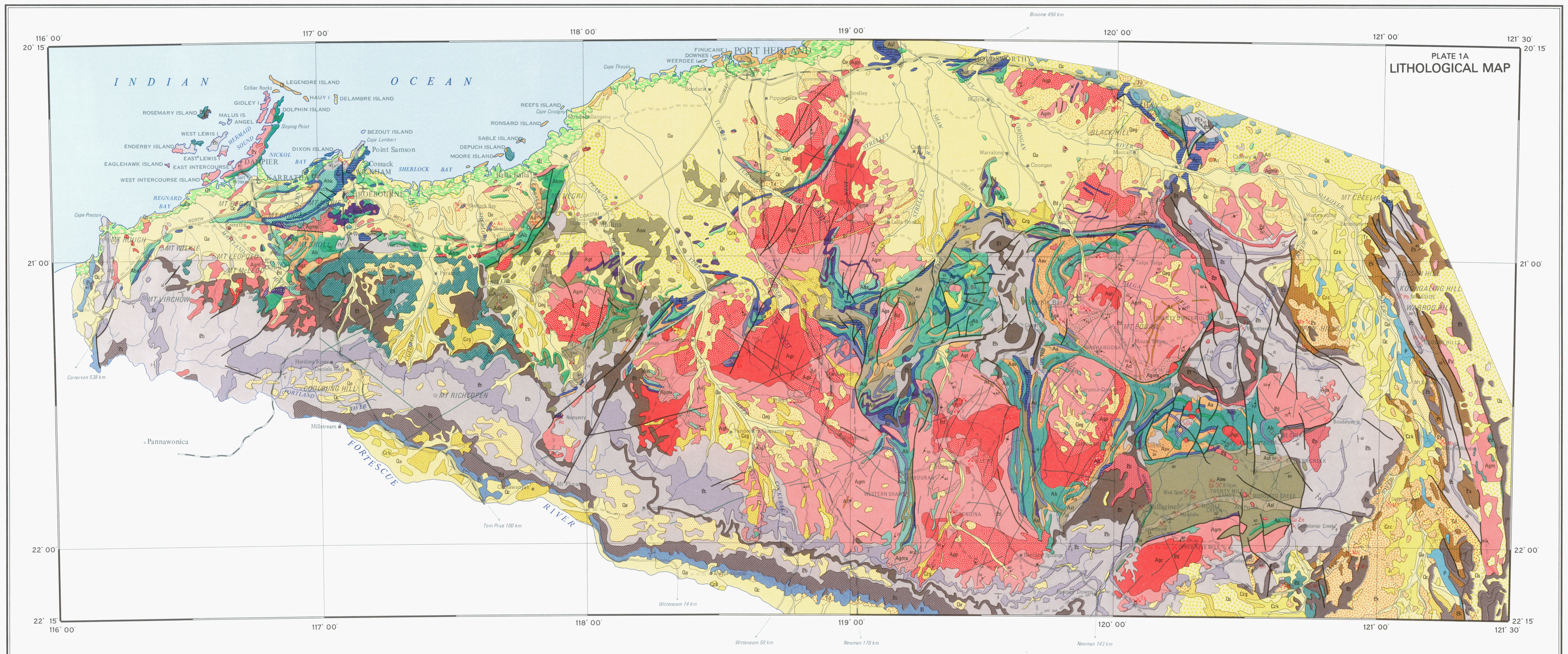
- AW — WARRAWOONA GROUP: (unsubdivided)
- AWw — WYMAN FORMATION: chiefly porphyritic rhyolite

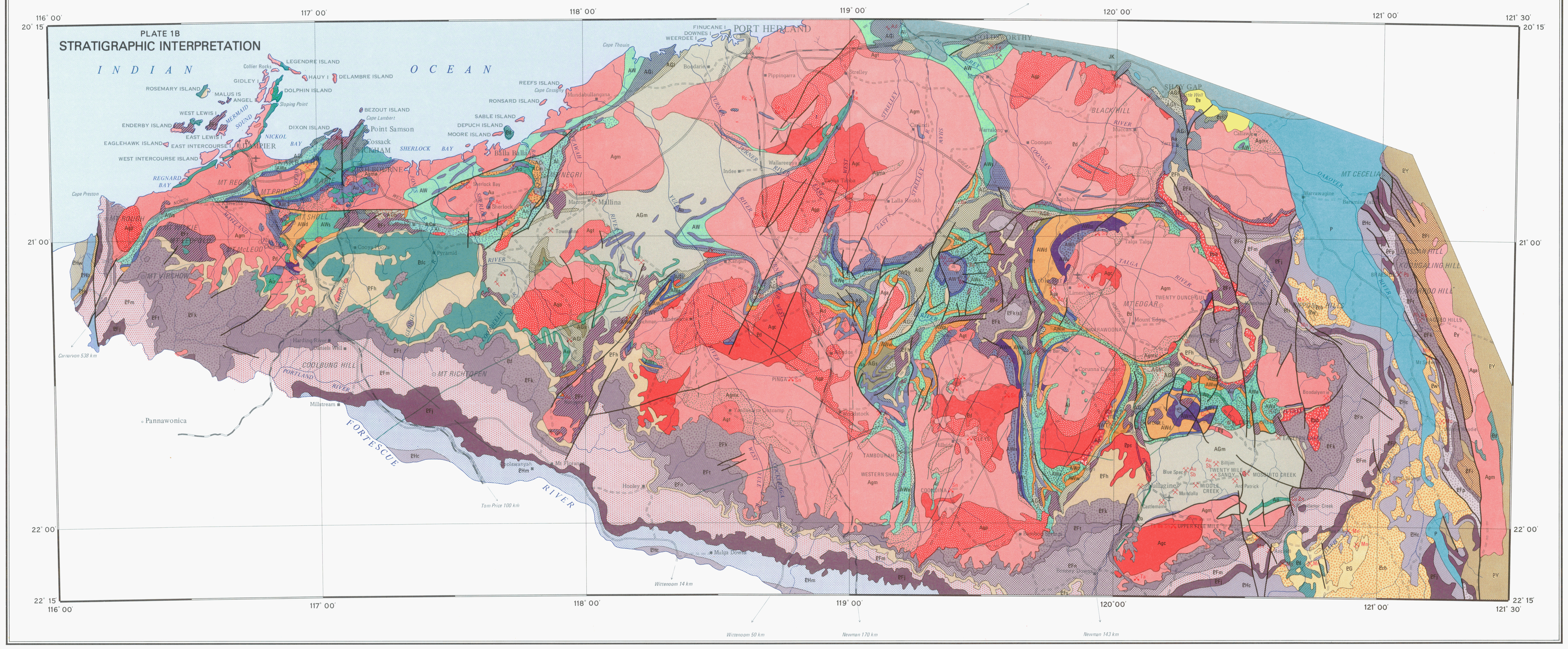
local unconformity

- AWs — SALGASH SUBGROUP
- AWe — EURO BASALT
- AWp — PANORAMA FORMATION: felsic volcanics and sediments
- AWa — APEX BASALT
- AWt — TOWERS FORMATION: chert, minor basalt (inc MARBLE BAR CHERT MEMBER)
- AWd — DUFFER FORMATION: felsic lava and pyroclastics
- AWT — TALGA TALGA SUBGROUP
- AWm — MOUNT ADA BASALT
- AWu — McPHEE FORMATION: ultramafics and sediments
- AWn — NORTH STAR BASALT

GRANITIC ROCKS

- Agc — Post-tectonic granite and adamellite
- Aga — Alkali-feldspar granite
- Agp — Porphyritic adamellite and granodiorite
- Agt — Granodiorite and tonalite
- Agm — Well foliated, gneissic, migmatitic adamellite and granodiorite
- Agmx — Numerous greenstone xenoliths in 'Agm'





LITHOLOGICAL MAP REFERENCE

CAINOZOIC

QUATERNARY

- Qa — Alluvium
- Qc — Colluvium
- Qs — Eolian sand
- Qe — Eluvium: gilgai over basalt, pebbly sand over Permian rocks
- Qt — Supratidal and intertidal clay and silt
- Ql — Sandy and shelly limestone
- Qeg — Eluvium over granitic rocks
- Czc — Colluvium and alluvium
- Czk — Calcrete
- Czg — Gravel

TERTIARY

- Td — Ferruginous duricrust
- Tp — Pisolitic limonite
- Tr — Siliceous cap-rock

MESOZOIC

- JK — Chiefly sandstone

PERMIAN

- P — Fluvioglacial deposits

PROTEROZOIC

INTRUSIVE ROCKS

- Ꝑo — Gabbro
- Ꝑd — Dolerite
- Ꝑr — Felsic rock of minor intrusions
- Ꝑg — Hornblende adamellite
- Ꝑy — Granophyre
- Ꝑp — Dacite porphyry

- Ꝑt — Limestone and pisolitic tuff. Includes stromatolites
- Ꝑb — Basalt and andesite
- Ꝑt — Sandstone and conglomerate
- Ꝑs — Shale and chert. Local carbonate rocks with stromatolites
- Ꝑk — Dolomite
- Ꝑa — Felsic volcanic rocks
- Ꝑi — Iron-formation (clastic)
- Ꝑx — Chert breccia
- ꝐEs — Sediments of uncertain age

ARCHAEAN

INTRUSIVE ROCKS

- Ao — Gabbro
- Ap — Felsic porphyry
- Ad — Dolerite
- Ar — Felsic rock of minor intrusions

- As — Sedimentary rock (not subdivided)
- Asf — Ferruginous clastic sedimentary rock
- Asl — Siltstone and shale
- Ast — Sandstone and conglomerate
- Asw — Psammitic to pelitic schist (includes turbidites)
- Ac — Chert : grey – white or red – white banded
- Aci — Banded iron-formation, jaspilite
- Aa — Felsic volcanic rocks
- Aav — Felsic agglomerate and tuff
- Ab — Basalt
- Aba — Amphibolite (after basalt and dolerite)
- Abm — Tremolite – chlorite rock. Includes magnesia-rich basalt
- Au — Ultramafic rocks (not subdivided)
- Aup — Peridotite
- Aux — Pyroxenite

GRANITIC ROCKS

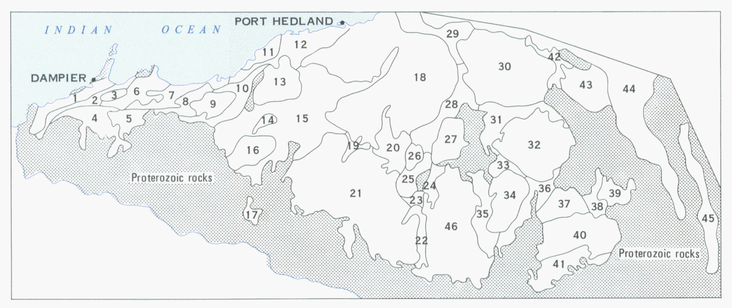
- Agc — Granite and adamellite. Poorly foliated and generally equigranular
- Aga — Alkali feldspar granite
- Agp — Porphyritic granitic rock
- Agt — Tonalite and granodiorite
- Agm — Biotite adamellite, granodiorite and tonalite. Typically foliated, gneissic or migmatitic
- Agmx — Numerous greenstone xenoliths in 'Agm'

SYMBOLS

- Geological boundary
  - Intrusive relationship
- Fault
- Bedding
  - Inclined
  - Vertical
- Foliation
  - Inclined
  - Vertical
- Highway
- Formed road
- Track
- Railway, standard gauge
- Townsite
  - Population 10 000 and over — PORT HEDLAND
  - 1 000 – 10 000 — DAMPIER
  - Under 1 000 — Point Samson
- Homestead — Woodstock
- Airfield
- Horizontal control
- Watercourse, intermittent

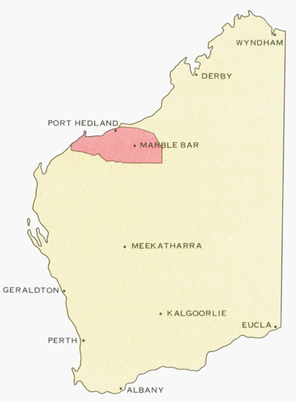
- Mining centre — WESTERN SHAW
- Mine — Blue Spec
- Prospect
- Open cut
- Alluvial workings
- Mineral occurrence
  - Antimony — Sb
  - Barite — Ba
  - Beryllium — Be
  - Chrysotile (asbestos) — Ac
  - Copper — Cu
  - Crocidolite (tiger eye) — Ad
  - Crushed rock aggregate — Rc
  - Fluorite — Fl
  - Gemstones — Gs
  - Gold — Au
  - Iron — Fe
  - Lead — Pb
  - Manganese — Mn
  - Molybdenum — Mo
  - Nickel — Ni
  - Salt (solar evaporation) — Na
  - Silver — Ag
  - Tantalum — Ta
  - Tin — Sn
  - Titanium — Ti
  - Tungsten — W
  - Vanadium — V
  - Zinc — Zn

MAJOR STRUCTURAL UNITS OF THE PILBARA BLOCK

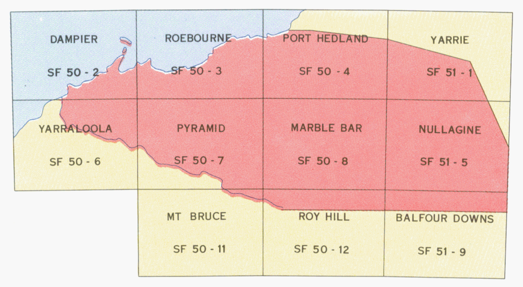


1 Dampier Batholith
2 Regal Belt
3 Karratha Granite
4 Chiratta Batholith
5 Sholl Belt
6 Roebourne Syncline
7 Harding Granite
8 Sherlock Belt
9 Caines Well Granite
10 Whim Creek Belt
11 Balla Balla Granite
12 Boodarie Belt
13 Portree Granite
14 Peawah Granodiorite
15 Mallina Synclinorium
16 Satirist Granite
17 Nunyerry Inlier
18 Carlindi Batholith
19 Wodgina Belt
20 Pilgangoora Syncline
21 Yule Batholith
22 Western Shaw Belt
23 Tambina Complex
24 North Shaw Belt
25 Soanesville Belt
26 Strelley Granite
27 North Pole Dome
28 Lalla Rookh Syncline
29 Goldsworthy Syncline
30 Muccan Batholith
31 Marble Bar Belt
32 Mount Edgar Batholith
33 Warrawoona Syncline
34 Corunna Downs Batholith
35 Coongan Syncline
36 Kelly Belt
37 McPhee Dome
38 Mount Elsie Belt
39 Yilgalong Granite
40 Mosquito Creek Synclinorium
41 Kurrana Batholith
42 Shay Gap Syncline
43 Warrawagine Batholith
44 Canning Basin
45 Gregory Granitic Complex
46 Shaw Batholith

LOCALITY DIAGRAM



INDEX TO 1:250 000 SHEETS



HON. P.V. JONES, M.L.A.
MINISTER FOR MINES
A.F. TRENDALL, DIRECTOR, GEOLOGICAL SURVEY

SCALE 1:1 000 000

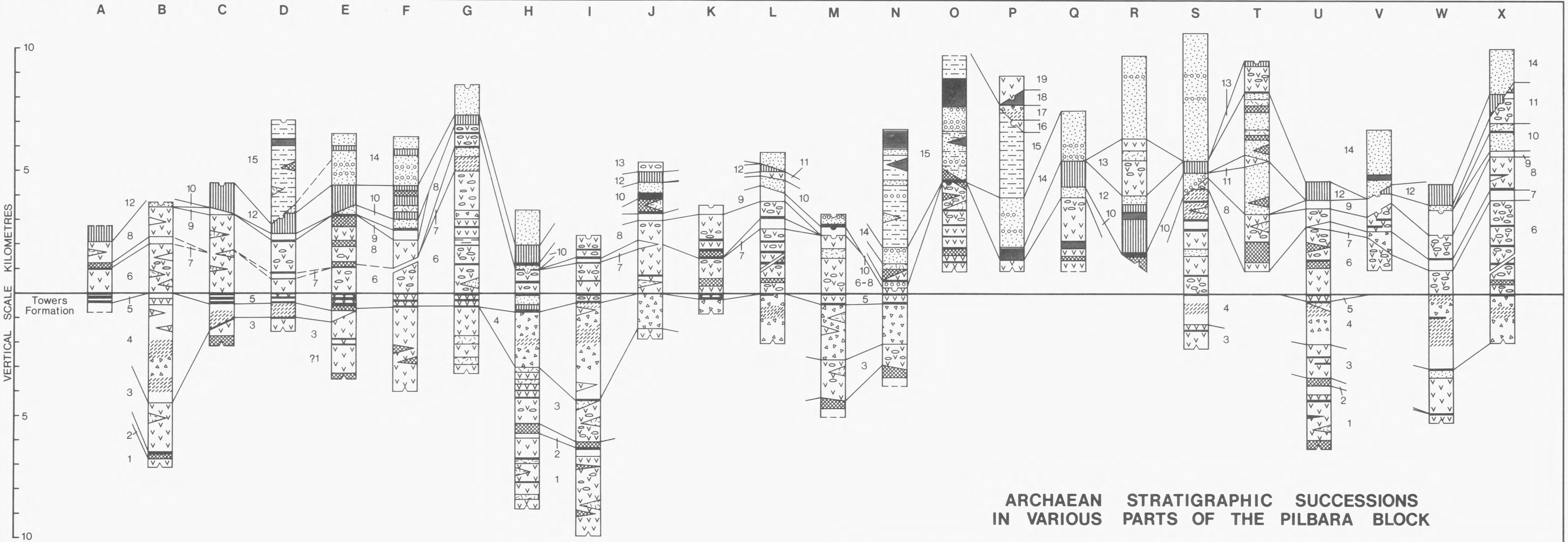
20 0 20 40 60 80 100 120 KILOMETRES

ALBERS EQUAL AREA PROJECTION WITH STANDARD PARALLELS 17°30' AND 31°30'S

Compiled and published by the Geological Survey of Western Australia. Cartography by the Geological Mapping Section, Department of Mines. Topographic base from compilations by the Department of Lands and Surveys.
Copies of this map may be obtained from the Geological Survey of Western Australia, 66 Adelaide Tce., Perth. Printed by the Government Printing Office, Perth 1980.

Geology by A.H. Hickman

LITHOLOGICAL MAP AND STRATIGRAPHIC INTERPRETATION OF THE PILBARA BLOCK



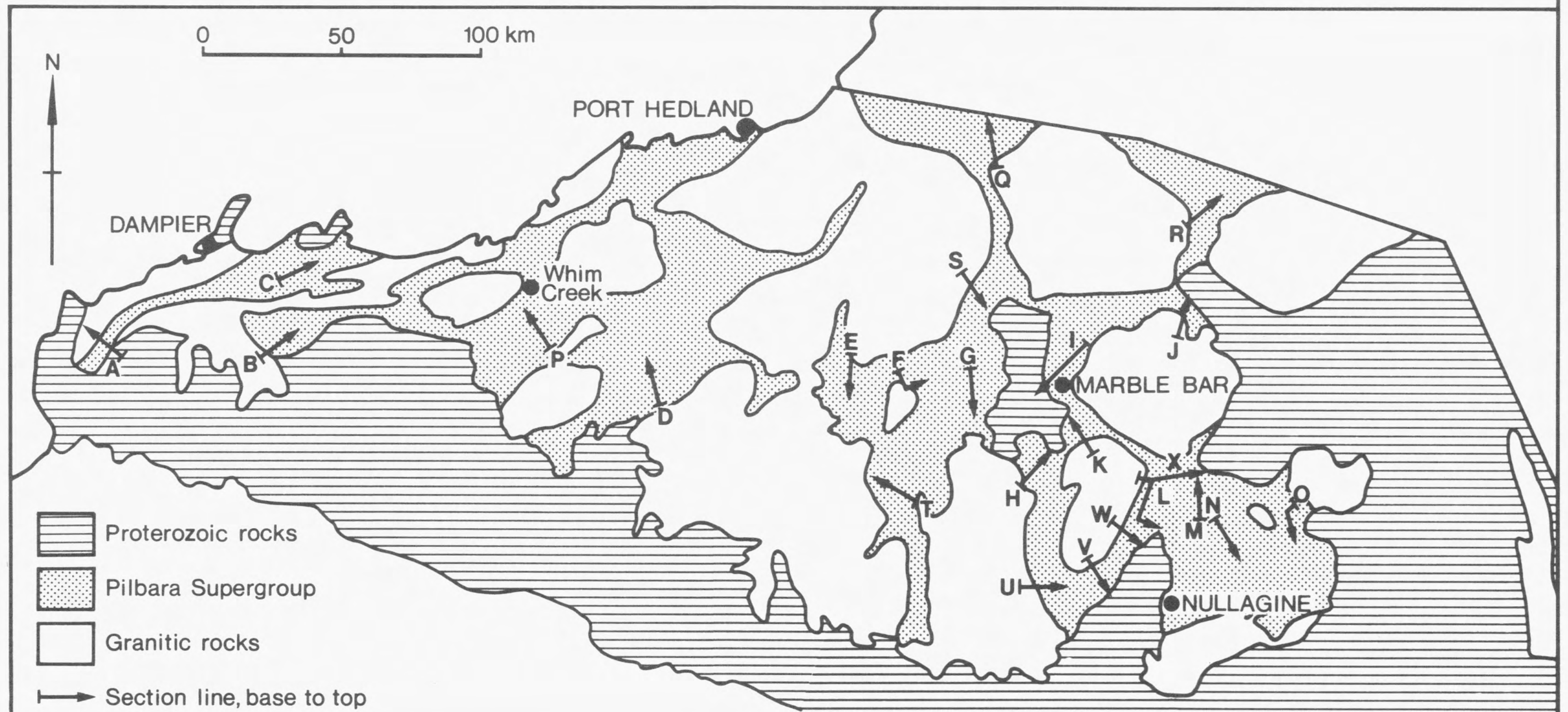
ARCHAEAN STRATIGRAPHIC SUCCESSIONS IN VARIOUS PARTS OF THE PILBARA BLOCK

REFERENCE

- Pelitic schist
- Psammopelitic schist
- Sandstone
- Conglomerate
- BIF and ferruginous sediments
- Chert
- Felsic lava
- Felsic tuff
- Felsic agglomerate
- Basalt
- Pillow basalt
- Dolerite/gabbro
- Ultramafic rocks
- Unconformity
- Break in succession

STRATIGRAPHIC FORMATIONS

1. North Star Basalt
2. McPhee Formation
3. Mount Ada Basalt
4. Duffer Formation
5. Towers Formation
6. Apex Basalt
7. Panorama Formation
8. Euro Basalt
9. Wyman Formation
10. Corboy Formation
11. Charteris Basalt
12. Cleaverville Formation
13. Honeyeater Basalt
14. Lalla Rookh Sandstone
15. Mosquito Creek Formation
16. Warambie Basalt
17. Mons Cupri Volcanics
18. Rushall Slate
19. Negri Volcanics



For exact locations of sections A to X see Appendix H

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