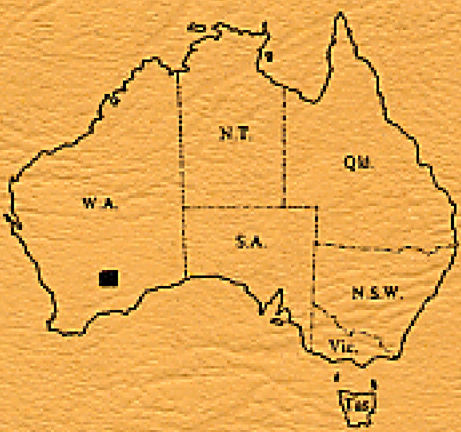
GEOLOGICAL SURVEY OF WESTERN AUSTRALIA

1:250 000 GEOLOGICAL SERIES—EXPLANATORY NOTES

# BOORABBIN

## WESTERN AUSTRALIA

**SECOND EDITION**




SHEET SH51-13 INTERNATIONAL INDEX

# WESTERN AUSTRALIA
## INDEX TO GEOLOGICAL MAPS
## SCALE 1:250 000

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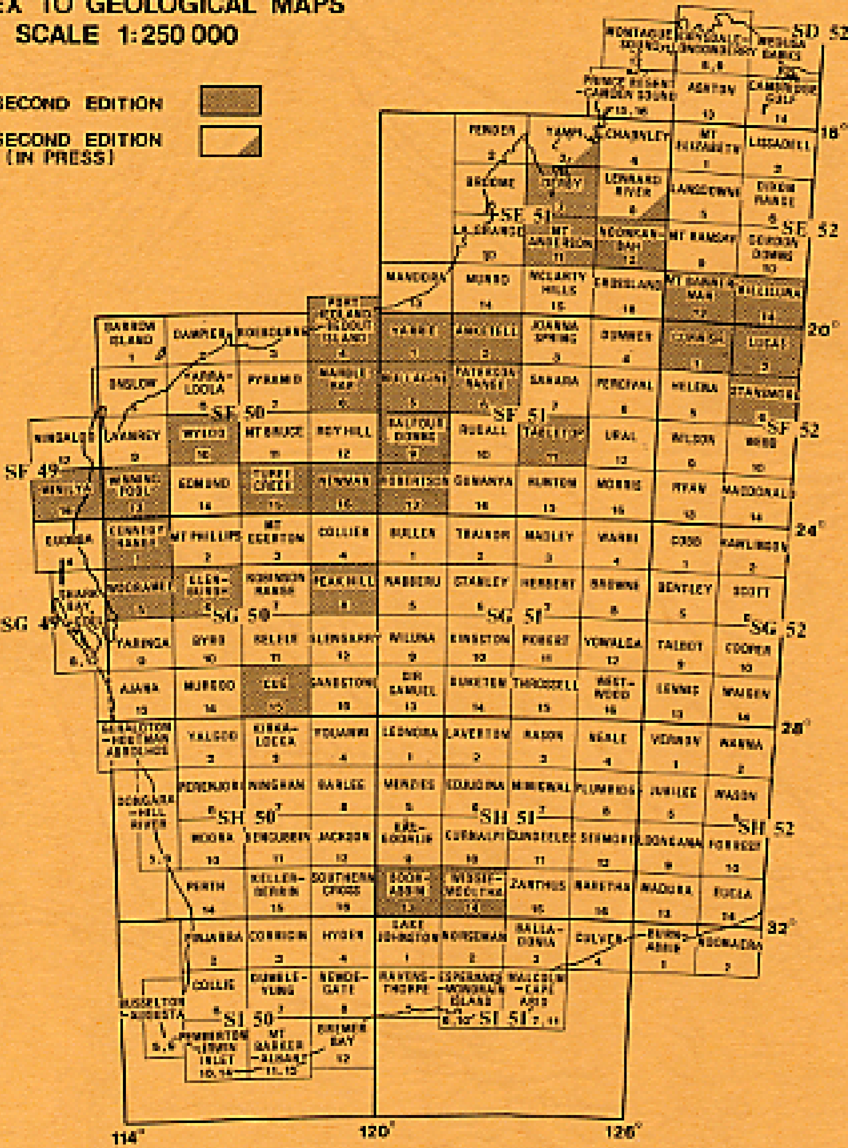

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# BOORABBIN

## WESTERN AUSTRALIA

**SECOND EDITION**

SHEET SH51–13 INTERNATIONAL INDEX

BY
W. M. HUNTER

PERTH, WESTERN AUSTRALIA 1991

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## CONTENTS





00857-2

## MAP



## FIGURES



## TABLES

# Explanatory Notes on the Boorabbin Geological Sheet Western Australia (Second Edition)

*by W. M. Hunter*

## INTRODUCTION

The BOORABBIN* 1:250 000 sheet (SH51–13) is bounded by latitudes 31°00′ and 32°00′S and longitudes 120°00′ and 121°30′E, and lies 450 km east of Perth. The area is within the Eastern Goldfields Province of the Yilgarn Craton (Williams, 1974b) and includes parts of the Coolgardie and Dundas Mineral Fields. The sheet derives its name (which translates to "a chain of water holes"; Reed, 1967) from a locality gazetted by C. C. Hunt in 1865.

Mineral exploration and mining co-exist with primary production in the northeast corner of BOORABBIN. Hampton Plains, Bali, Woolibar, Calooli and Bullabulling Stations are occupied, but Horse Rocks Station and land west of the Coolgardie–Norseman Highway (part of Mandilla Station) have reverted to Crown land. The remainder is vacant Crown land, which was extensively exploited for timber in the first half of this century. Straddling the highway, between Koorarawalyee and Boorabbin, is the Boorabbin National Park (part of System 11); flora and fauna reserves are located at Queen Victoria Rocks, Burra Rock, Cave Hill, and west of Baker Lake (Jilbadji). Forest reserves are situated in the Kangaroo Hills, Saddle Hills, and Horse Rocks areas.

Access throughout BOORABBIN is generally poor. The Great Eastern and Coolgardie–Esperance Highways cut the northwest and northeast of the sheet, respectively; an unsealed, but well-formed, road passes through the centre of the area, linking Coolgardie with Hyden. The Muja–Kalgoorlie 220 kV power line, the Mundaring–Kalgoorlie water pipeline, and the abandoned Perth–Kalgoorlie narrow-gauge railway run parallel to the highway in the northwest. Access to the remainder of BOORABBIN is by sparse, poorly defined tracks blazed by early explorers and timber cutters. A network of abandoned "woodlines" covers the eastern and northern parts of BOORABBIN. The remnant "formations" to these narrow-gauge railways have produced distinct photolineaments and are useful aids to navigation.

There are no townships on BOORABBIN; the administrative centre for this sheet area is Coolgardie, which lies 5 km north of the sheet boundary. A small minesite settlement exists at Nepean, and individual dwellings are found at Bullabulling, Hampton Plains and Spargoville. At Dedari, a small community services the water-supply pipeline and pumping stations.

## PREVIOUS INVESTIGATIONS

A bibliography of the early geology and exploration of Western Australia was compiled by Maitland (1899). Various geological investigations by the Geological Survey of Western Australia (GSWA) in the vicinity of BOORABBIN have been published (McMath et al., 1953, p. 33–35). Other important GSWA bulletins are: Blatchford

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* Map sheet names are printed in capitals to avoid confusion with similar place names.

(1899, 1913), Honman (1914), Feldtmann (1925), and Jutson (1950). More recently a review was made by Williams (1974c) "of the geological investigations of the Eastern Goldfields Province", and includes a bibliography up to December 1972.

The first regional geology survey at 1:250 000 scale was completed by Sofoulis and Bock in 1963, and the Bureau of Mineral Resources published the results of an aeromagnetic survey over BOORABBIN in 1965.

Since 1965, the region has been intensely explored, first for nickel and other base-metals and, more recently, for gold. The results of this exploration, given in statutory reports, are available for perusal from the "open-file" system of the Geological Survey. A synthesis of the geology revealed during the "nickel boom" exploration was made by Gemuts and Theron (1975). Their regional map and sequential stratigraphy provided the first refinement to the cyclical stratigraphic model of Williams (1969, 1971, 1974a). More recent work (e.g. Griffin et al., 1983) tends to favour complex structural repetition of simple, possibly single, sequences rather than the earlier polycyclic models.

## PHYSIOGRAPHY

BOORABBIN (Fig. 1) is in the south central portion of the Salt Lake or Salinaland division of Jutson (1950) and lies within the Wheat Belt and Kalgoorlie Natural Regions of Clarke (1926).

On the basis of vegetation, soil association and physiography, Beard (1976) divided the sheet into four "vegetation systems". The northwestern two-thirds (the Boorabbin System) is a weakly dissected upland developed on granite. This is the "Old Plateau" of Jutson (1950); it comprises undulating sandplain up to 500 m in altitude and valleys down to 380 m. Small low-lying outcrops of granite are scattered throughout the area, but they are most common under laterite scarps on the western margins of major trunk drainages (the "New Plateau").

The southeastern third of the area (the Cave Hill System) is also granitic upland with summits of similar altitude to the Boorabbin System. However, strong dissection has removed much of the sandplain cover of the "Old Plateau", producing narrow, deep valleys and exposing low granite hills as interfluves. Individual hills may have relief greater than 50 m although the general altitude range is from 300 m in the trunk drainage to 480 m over some peaks.

The northeast and southwest corners of the area (the Coolgardie and Bremer Range Systems) consist of north-northwest–trending ranges of hills, with relief of about 100 m. Rocky summits and broad talus flanks are composed of mafic and ultramafic volcanic rocks, and felsic volcaniclastic rocks. Internal and external drainage is complex and mainly fault controlled.

A study of the early Cainozoic drainages (van de Graaff et al., 1977) and interpretation of Landsat imagery reveals that the major drainage divide of southern Western Australia passes almost north–south through the centre of BOORABBIN. This modifies the view of Beard (1976) that the division had a more southwesterly trend. The divide, which has an elevation of 480–500 m within BOORABBIN, separates the north and westerly flow of the "Boorabbin Palaeoriver" system from the easterly flow of the "Lefroy Palaeoriver" (Fig. 1). The major trunk drainages, and abundant minor divides and interfluves are evidence of an ancient period of high precipitation. The waning of this pluvial regime and onset of an arid to semi-arid climate caused choking of drainage by sediments (aeolian and fluvial) and the development of the current playa-lake systems.

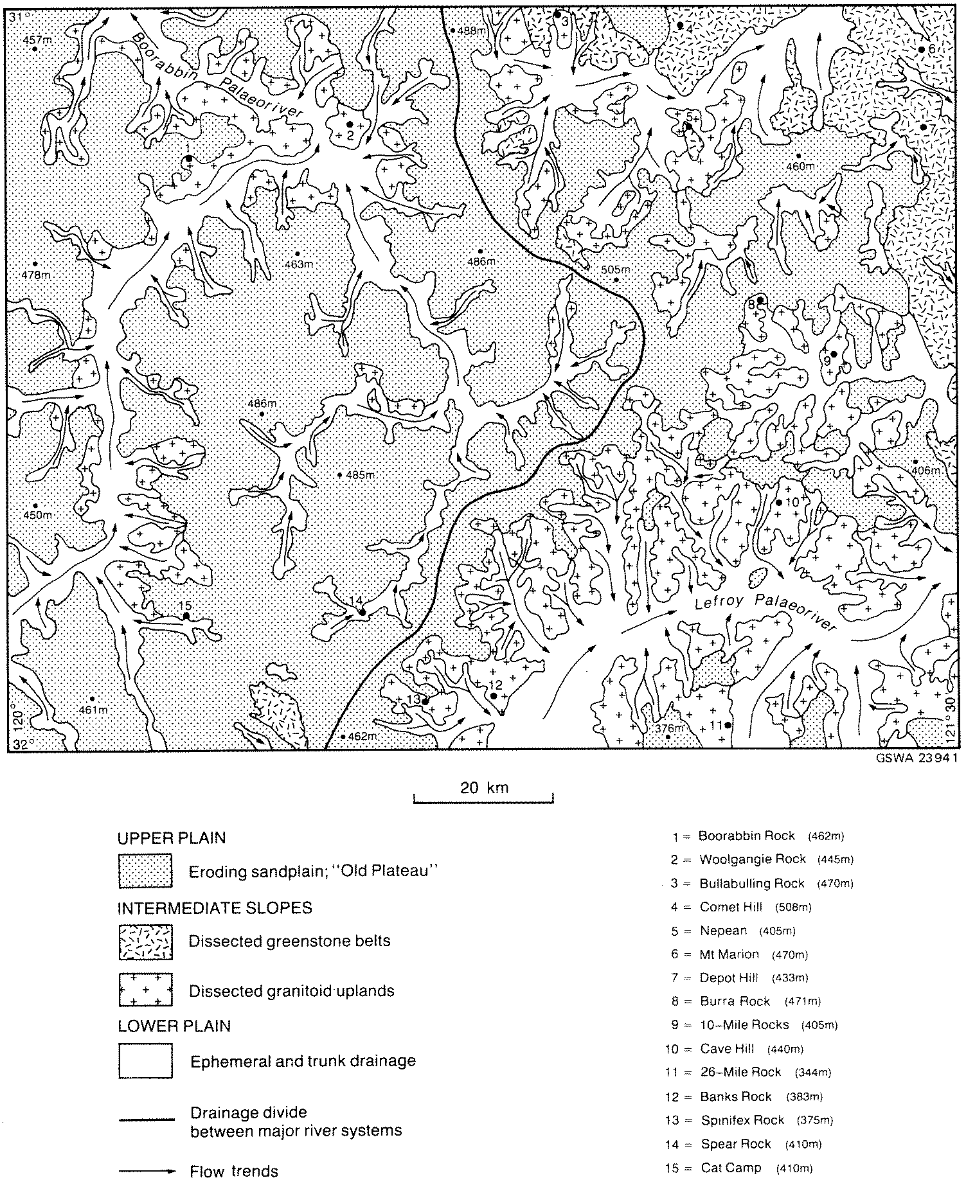


**Figure 1. Physiographic features of BOORABBIN**

Dating of the drainage systems is imprecise, but van de Graaff et al. (1977) have argued that significant flow ceased between late Eocene and mid-Miocene. The maximum age is certainly post-Early Cretaceous to the east, but there is evidence within the Precambrian shield area of a Permian age for some systems. The characteristic tear-drop shape of the playa lakes is controlled partly by basal geology and partly by the prevailing wind direction. Erosion is active on the western margins of these lakes while aeolian deposition occurs on the eastern margins.

The region has a semi-arid climate with hot summers and cool to mild winters. Average diurnal temperature ranges, measured at Coolgardie, are greatest in January–February (34–17°C) and least in July (16–5°C). Rainfall averages 250 mm a year with the wettest period being March–August. Evaporation greatly exceeds precipitation for most of the year and, in the northeast of BOORABBIN, averages 2200 mm a year.

There is a close correlation between photo-interpreted geology and the six "plant formations" delineated by Beard (1976), since the success of floral species is strongly controlled by soil type. "Scrub Heath" and "Broombush Thicket", popularly called sand heath and tamma scrub, form on leached sands (*Czs*), shallow lateritic soils (*Czl*), and degraded granite outcrops (*Ag*). Mixed, stratified, partly open shrub assemblages, of Protaceae and Myrtaceae grade to less diverse, single-layered, very dense shrub assemblages of *Casuarina, Acacia,* and *Melaleuca.* "Rock Pavement Vegetation" consists of lichen and moss on bare outcrops of granite (*Ag*), aquatic plants in pools, and shrubs in crevices or occasional soil patches. On leached granite eluvial (*Czg*) and colluvial (*Czc*) soils, "Mallee" and "Sclerophyl Woodland" form open to closed eucalypt shrub or woodland with variable low-shrub ground layer. Communities of salt-tolerant "Halophytes" (e.g. saltbush—*Atriplex*, and samphire—*Arthrocnemum*) occupy deposits bordering playa lakes (*Czts* and *Cztd*).

## ARCHAEAN GREENSTONES

Greenstones, which form the western boundary of the Norseman–Wiluna Belt, occur on the eastern margin of BOORABBIN (Fig. 2). Small inliers also occur scattered throughout the granitoid terrain. Contact relationships with basement rocks are unknown, but the greenstones are inferred to overlie the oldest granitoid, which is a streaky leucogneiss (*Anst*) (Fig. 3) occurring in southeast BOORABBIN.

All the greenstones have undergone several stages of pervasive deformation and metamorphism, and are both intruded by and separated by granitoid. Regional metamorphism reached at least lower-amphibolite facies, but primary textures are widely preserved and enable many protoliths to be readily identified. Therefore, for convenience of description, the prefix "meta-" has been omitted where the protolith can be identified.

The similarity of lithologies and local successions between greenstone belts leads to the inference that they are of similar age. They may have been continuous before being separated by granitoid intrusion.

The usage of some lithological terms is commonly debated; those used in these notes are defined here. Komatiites are extrusive rocks with high-magnesium and low-aluminium chemistry which commonly display distinctive mineral textures (Arndt and Brooks, 1978; Arndt and Nisbet, 1982). High-Mg basalts are closely associated with komatiites; they are moderately rich in magnesium and display characteristic textures. Volcaniclastic rocks include all clastic volcanic material regardless of the processes of fragmentation, dispersion, and deposition (Fisher and Schmincke, 1984).

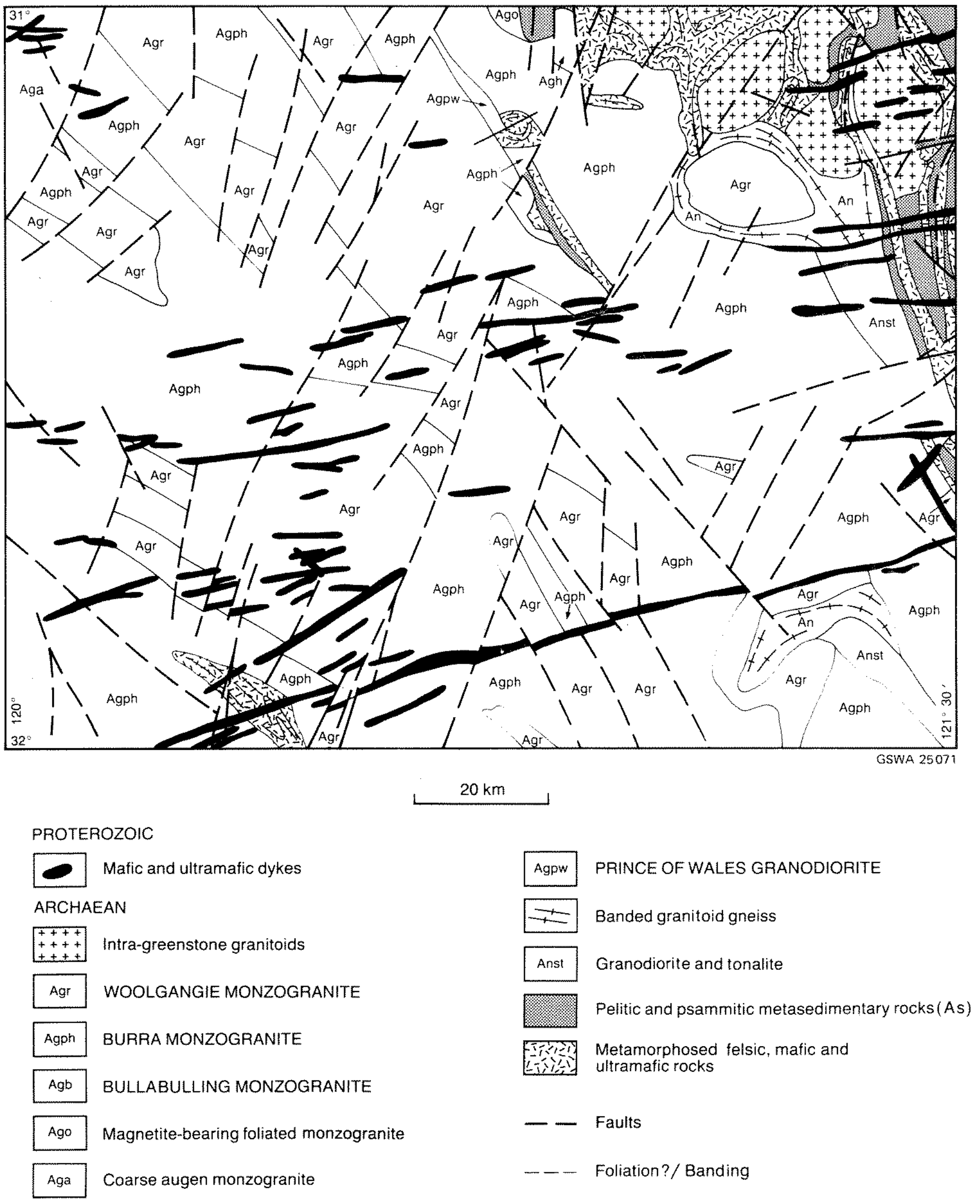


**Figure 2. Solid geology of BOORABBIN**

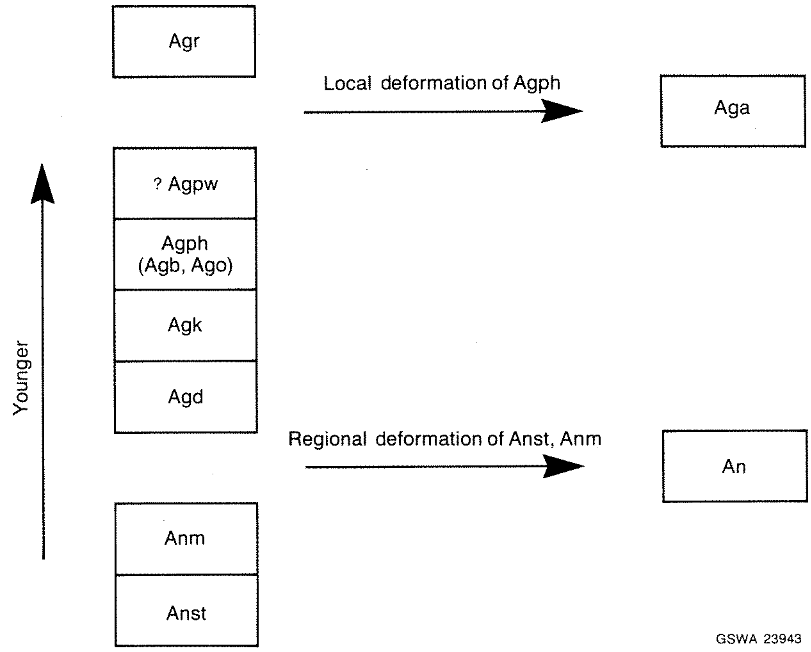


**Figure 3. Sequence of granitoid emplacement on BOORABBIN**

## EASTERN BOORABBIN

### Basalt (*Ab*)

Descriptions of the major basalt types are given below and subdivided according to the map symbol used. The general symbol *Ab* is used to indicate complexly interleaved basalts and minor intrusives or composite schists of these units.

### High-Mg basalt (*Abm*)

Thick sequences of mainly high-Mg basalts (*Abm*) containing thin interflow sediments occur throughout the greenstones of BOORABBIN. The sequence is at least 500 m thick in the Coolgardie area but in the Saddle Hills it approaches 1500 m. The thickness cannot be estimated in other belts because of the degree of structural complexity.

High-Mg basalt is overlain by a thick ultramafic succession, the boundary between them being marked by a grey shale horizon. The base of the basalt is not exposed and the underlying rock is unknown.

These basalts are fine to medium grained, and are dark green to black which weathers to pale or mid green. They occur in thin and laterally extensive flows, which contain pillow structures up to 50 cm across in the upper portions (1–5 m) of flows. The pillows are outlined by millimetre-scale bands of metamorphic chlorite, feldspar and amphibole, that have replaced rinds of chilled magma or vitric fragments. Further, there is textural, and commonly mineralogical, contrast between pillows and interstices.

Ocellar structures (Arndt and Nisbet, 1982) up to 1 cm across are scattered within massive horizons of basalt or in concentric zones within pillows. Variation in the size of ocelli occurs radially in some pillows. Ocelli generally show internal, concentric or radial zoning.

Flow-top breccias form sparse, thin (<0.5 m) horizons of small blocks (10–20 cm) set in a matrix of fine fragments of chilled lava or vitric shards. Southwest of Bakers Find, such breccia horizons have been conduits for late-stage hydrothermal fluids which have coated fragments with azurite and malachite.

The basalts contain a large proportion of mafic grains, which supports the interpretation of these being high-Mg basalts. Samples with a lower "colour index" correspond to more differentiated, doleritic flow cores. Metamorphic grade ranges from low- to mid-amphibolite facies but a few samples are possibly in upper-amphibolite facies. Both along and across the greenstone belts, the style of metamorphism varies between "static" and "dynamic", and textures vary from granoblastic through interlobate to polygonal. The degree of textural equilibrium attained appears to be related, in part, to the conjuncture of thermal and late-dynamic metamorphism and, in part, to the relative extent of tectonic uplift.

The rocks comprise amphibole and plagioclase with variable proportions of epidote, chlorite, quartz and carbonate; and accessory magnetite, ilmenite, sphene, and apatite. Amphibole constitutes 75–90% of the rock, although in the more differentiated varieties amphibole may be as low as 60%. Actinolite is the most common amphibole, but more hornblendic varieties occur locally. In the southern Karramindie belt and the area north of Spargoville, hornblendic amphibole is predominant where there is also evidence of a high degree of textural equilibrium in both static and dynamic styles.

Plagioclase constitutes up to 25% of the rock and ranges in composition from oligoclase to labradorite. Twinning is variably developed and zoning is uncommon. Plagioclase and quartz form a granular groundmass of irregular interstitial tracts, or pseudomorphs of bladed protocrysts. Grains are generally equant and form interlobate to polygonal mosaics.

Ocellar structures tend to have the same mineralogy as the hostrock but contain more plagioclase (50–60%). They show concentric variation in mineral proportions and grain size. The textures commonly mimic those of the hostrock where plagioclase has complex intergrowths with acicular or skeletal amphiboles. The boundary of the ocellar structures is generally sharp, despite recrystallization. Quartz and carbonate may also be present.

Metamorphic amphibole forms single crystals, multiple blades, or trains of granular crystals that pseudomorph original plumose pyroxenes. With progressively higher strain, fronds of these structures become rotated into parallelism and define schistosity; however dusty opaques exuded from pyroxenes during recrystallization commonly preserve the form of protocryst. In those rocks with more basaltic or doleritic textures, broadly bladed or subophitic, platy pyroxenes are pseudomorphed by multigrain plates or granular masses of amphibole.

Apparent grain-size coarsening occurs in the chilled lava portions of pillows south of Spargoville. Amphibole grows as fine, short needles in "bow-tie" sheafs or rosettes up to 5 mm across. In the field, these appear to be pseudomorphs after equant platy (gabbroic) pyroxenes; however, occelli commonly detail pillow forms and reveal the nature of the protolith.

In the Gibraltar and Prince of Wales areas, pale-green to pale-brown cummingtonite–grunerite dominates lineated schistose metabasalts, which are strongly recrystallized and have good equilibrium textures.

*Discussion*

High-Mg basalts are identified by colour, density, and mineralogy. They are characterized by fine plumose or variolitic textures and, more rarely, pyroxene-spinifex textures (Campbell and Arndt, 1982). Pillow and ocellar structures are abundant.

In the Spargoville–Larkinville region, microgabbro to gabbro pseudo-textures have been produced by overgrowths of metamorphic amphibole.

The presence of tholeiitic basalts in this area has long been mooted (Hallberg, 1972; Gemuts and Theron, 1975), but nowhere are they unequivocally demonstrated. If they do occur, then they are subordinate to the more easily identified high-Mg basalts. Zones of "dolerite" have, in the past, been mapped within basalt as swarms of sills or as interbedded tholeiitic basalts. In the Saddle Hills, where they form at the centre or towards the base of flows, it is clear that such zones are variations within flows of high-Mg basalt. The extent to which the zones develop appears directly proportional to the thickness of the flow. These "dolerites" are interpreted as zones of slower cooling and of differentiation within flows.

Deformation of the basalts produced spaced occurrences of high strain. In thick zones of apparent low strain, such as the Burbanks and Saddle Hills areas, deformation was taken up along interflow beds of grey shale. Elsewhere, deformation produced pervasive layer-parallel foliation, which may be intense (Spargoville–Larkinville), or moderate (Grosmont, Karramindie North). In the southern half of the Karramindie belt, shearing has produced compositionally banded amphibolites derived from (?)quartz-veined pillowed basalts. Primary structures, such as ocelli and pillows, have been flattened and, commonly, elongated, to form a sub-vertical lineation.

Two thin marker horizons occur in the upper portions of the basalt sequence. The lower is a feldspar-phyric basalt, which is described fully in a later section. Approximately midway between this unit and the overlying ultramafic lavas there is a very thin, poorly outcropping layer of mixed "sediments" comprising interbedded grey shale and felsic porphyry schist. This unit is auriferous and its outcrop is marked by lines of old gold workings.

## Basaltic agglomerate (*Aba*)

Agglomerate to lapilli tuff (*Aba*) occurs 3 km northwest of Karramindie Soak. The unit is up to 500 m thick, of limited lateral extent, and is bounded by a mylonitic shear zone to the east. It overlies high-Mg basalts and is overlain by grey shales and felsic volcaniclastic rock. Horizons of crystal and lithic tuff occur sparsely throughout the area, although they are commonly difficult to recognize in deformed high-Mg basalts because of their similarity to flow-top breccias.

The agglomerate contains subangular to rounded clasts of basalt, dolerite and felsic volcaniclastics, and occasional fragments of fine- to medium-grained amphibole-rich tonalitic granitoid. The proportion of felsic rocks increases gradually upward while that of mafic rocks increases downward. The clasts seldom exceed a few centimetres, and the size distribution is polymodal. Clasts are elongated subparallel to an upright anastomosing foliation which is more strongly developed in the matrix than in the clasts.

The basalt fragments have internal flow structures, amygdales, and fine plagioclase phenocrysts. Foliation is confined to the margins of clasts where they abut a moderately foliated matrix. The rock contains hornblende, quartz, andesine, and scattered grains of opaque minerals and apatite. Retrograde metamorphism, probably related to the intrusion of the Karramindie Monzogranite, has introduced rare, yellowish pumpellyite. The general texture, particularly for plagioclase, is granoblastic, polygonal to interlobate; although amphibole forms felted masses. The matrix is a fine- to medium-grained, foliated, hornblende-bearing tonalite. Similar textures and metamorphic grade indicate that this granitoid matrix was metamorphosed at the same time as the basaltic clasts it supports.

This agglomerate deposit is unusual in having a matrix comprising a mixture of rock types. Several occurrences of fragmental basic rocks, associated with felsic hosts, have been described on KALGOORLIE (Hunter, in prep.). They occur both at this stratigraphic level and part-way up the felsic volcaniclastic pile.

Northwest of Karramindie, the intimate association of felsic and basic igneous rocks indicates that they were contemporary, and that magma confluence caused explosive eruptions and the ejection of mechanically mixed pyroclasts. Macroscopic and microscopic textures show primitive development of plagioclase phenocrysts and amygdales. None of the characteristic textures of high-Mg basalts have been seen. The source of the basaltic magma was probably the same as that of the feldspar-phyric basalt (*Abp*).

## Porphyritic basalt (*Abp*)

Within the upper levels of the high-Mg basalt sequence a feldspar-phyric basalt (*Abp*) forms a distinctive marker horizon which early prospectors titled "cat-rock" (alluding to the mottled coat of a native marsupial). The unit is well exposed near Burbanks and in East Location 59, but becomes progressively obscured by deformation and recrystallization southward. Porphyritic basalt has not been recognized south of Saddle Hills.

Porphyritic basalt has a maximum thickness of 200 m near Burbanks. Contacts with high-Mg basalt are sharp, but there are no apparent chilled margins. Textural variation occurs on a regional scale, although the basalt appears to be a single unit.

The matrix ranges from fine to coarse grained on a regional scale but the size and abundance of feldspar megacrysts varies from exposure to exposure. Phenocrysts occur up to 2 cm in length and are euhedral to subhedral. They characteristically agglomerate as clusters of many (commonly 4 to 6) crystals, only occurring as individuals when they are scarce.

The porphyritic basalt is compositionally closer to tholeiite than to high-Mg and has, therefore, greater affinity with the gabbro sills (*Aog*) of this area. Except in zones of high strain, igneous textures are commonly preserved, but evidence to indicate flow or small intrusion is equivocal.

Hornblendic amphibole occurs as acicular to prismatic crystals, which are in some areas sieved. Andesine occurs as fine laths in the matrix and as euhedral megacrysts. Deformation has induced a fine granulation in plagioclase which tends towards polygonal mosaics. Phenocrysts are well preserved in low-strain localities, otherwise they are recrystallized to subgrains within protocryst boundaries. A characteristic feature of these metamorphosed glomerophenocrysts is the overgrowth of amphibole. Bundles of fine parallel needles nucleate at crystal boundaries and invade the megacrysts. Total replacement occurs locally (e.g. southwest of Burbanks) and has produced dark mottles in the rock, which, when strained, appear as streaky dark augen. Scattered grains of magnetite, quartz, biotite, leucoxene, clinozoisite, and carbonate are present.

The value of porphyritic basalt as a marker horizon is uncertain as it is not clear whether this unit is wholly intrusive or extrusive (Blatchford, 1913; Ward, 1948; Miles, 1946; McMath, 1950; Sofoulis and Bock, 1963). South of Coolgardie, porphyritic basalt (*Abp*) forms a thin, continuous unit at the same stratigraphic level throughout, and there is no evidence of transgression or bifurcation. Hunter (in prep.) has interpreted pillowed porphyritic basalt on KALGOORLIE as a high-level intrusive.

### Komatiite (*Aku*)

Ultramafic extrusive rocks (*Aku*) occur throughout BOORABBIN, and reach a maximum thickness of 600 m. Where greater thicknesses are apparent, for example northeast of Burbanks, major and minor isoclinal folds have repeated the stratigraphy. Intense deformation (such as that which has occurred near Spargoville) has diminished the thickness of komatiite, which is less competent than adjacent rocks. In shear zones, such as northwest Saddle Hills, the thin layers of ultramafic schists (*Au*) are derived from attenuated layers of komatiite.

Komatiite forms extensive laterally uniform flows, and thickness varies from flow to flow (5–30 m). The flows are laterally homogeneous but have vertical variations in texture and composition. They are overlain by felsic volcaniclastic rocks and underlain by high-Mg basalts. Both boundaries are marked by a thin bed of grey shale (see "Marker horizons").

Komatiite (*Aku*) displays a variety of textures and mineralogy which indicate its origin as extrusive rock crystallized from an ultrabasic liquid (Viljoen and Viljoen, 1969a, b; Arndt et al., 1979; Arndt and Nisbet, 1982). Most conspicuous is the development of textural layering within individual flows: zones of bladed olivine crystals in intermeshed or sheaved aggregates ("spinifex textures") overlie zones of granular, cumulate olivine ("dunite").

Pillow structures (0.1–1 m), whose shapes are defined by narrow (2–10 mm) dark rinds of recrystallized glassy material and interstitial hyaloclastite, occur sporadically. Ocellar structures and random-spinifex textures may form in otherwise homogeneous pillows (e.g. on the eastern margin of the Saddle Hills).

Komatiite contains tremolite, chlorite, talc, serpentine, and traces of magnetite, carbonate minerals and phlogopite. There are localized occurrences of anthophyllite–chlorite and talc. Platy and plumose spinifex textures are well preserved in domains of low strain where tremolite forms both single and multi-grain pseudomorphs of original macrocrysts. Similarly, the granular texture of cumulate olivines in basal dunite is also preserved. Within a spinifex-textured sequence, the relative proportions of metamorphic minerals varies; for example, talc predominates in dunitic basal cumulates.

Metamorphism accompanying deformation tends to obliterate igneous textures; however, trains of exsolved magnetite which delineated original skeletal crystal forms may be preserved. Spinifex-textured komatiites can be traced into strained zones and the progressive textural modifications towards tremolite–talc schists observed. Oblate rosettes of tremolite nucleate at the boundaries of spinifex macrocrysts, and orient in spaced bands parallel to the foliation.

### *Marker horizons*

*Shale*: The shale beds are 1–5 m thick and laterally extensive. They are commonly graphitic or tuffaceous and may show internal compositional banding; bands are locally rich in quartz, iron oxides, or tourmaline. Folding within beds is due in part to soft-sediment slumping but also to deformation during folding. Localized near-surface silicification of the shales has produced cherty horizons that are resistant to weathering.

*Basalt*: One-half to two-thirds of the way up the komatiite pile is a 100–150 m thick basaltic marker horizon. Only one such horizon is known and is laterally persistent. Multiple occurrences of the horizon, such as 5 km north-northeast of Burbanks, are interpreted as repetitions by isoclinal folding. Contacts with the komatiite are sharp at the top but may be sharp or gradational at the bottom. Internal boundaries may indicate that a number of flows are present. Grain size variations can be seen at particular localities, and between localities. The variation is from medium to coarse, and, locally, very coarse. No chilled margins are apparent.

There are textural and compositional similarities between this basalt and high-Mg basalts; however, it contains dark, iron-rich actinolite or hornblende, rather than more magnesium-rich amphibole. It is characterized by acicular pyroxene-spinifex textures in the coarser grained units, or stellate to plumose intergrowths of pyroxene and plagioclase in the finer grained horizons.

### *Discussion*

Throughout BOORABBIN, komatiite shows well-developed spinifex-textured sequences. These range from granular cumulate bases; through oriented, bladed megacrysts and random, fine bladed crystals; to glassy flow-top breccias. Not all flows show the full textural sequence. There is some correlation between the extent of spinifex development and flow thickness, which suggests control by cooling rate. In some high-strain zones, the stress was taken up preferentially in the cumulate layers at the base of flows. There, coarse spinifex is isolated by narrow (5–50 cm) bands of talc schist. Elsewhere, attenuation was more general, and produced thick zones of ultramafic schist.

Skeletal spinifex textures and granular cumulate textures are generally attributed to different cooling rates within the flow (Arndt and Nisbet, 1982). In recent studies of komatiites north of Kalgoorlie, Hill et al. (1987) proposed that the degree of supercooling and chemical composition of the lava are important in the generation of these textures.

The ultramafic rocks of the Eastern Goldfields were extensively examined for nickel deposits and many detailed descriptions of prospective areas exist. These areas have been summarized by Groves and Lesher (1982), and Marston (1984); they are further discussed in the economic geology section of this report.

The presence of sediments within the komatiite pile indicates fluctuating conditions of volcanism and quiescence. South of Spargoville, there is evidence of a lava having flowed over still-wet sediments: volatilization of water caused turbulent mixing of komatiite and shale, which resulted in a 2–5 m thick heterogeneous layer with relict textures and mineralogy of both lithologies.

The origin of the basalt is uncertain; however, it appears to be intimately related to the surrounding komatiites. Field and textural evidence indicate that the basalt is extrusive and, therefore, represents a modification in the chemistry or crystallization history of the komatiite magma.

The basaltic marker horizon is significant not only for its value in tracing the local structure and stratigraphy, but also for its economic potential. The upper contact with komatiite, particularly when intruded by one or more felsic porphyry intrusions, is a common location for gold deposits and is therefore a good exploration target. Figure 4 shows which gold occurrences are found at this stratigraphic level.

### Felsic volcaniclastics and sediments (*As*, *Aft*)

A complex succession of volcanic, clastic, and intrusive rocks of felsic affinity (*As*, *Aft*) (maximum thickness about 1500 m) occurs throughout the greenstone belts of BOORABBIN. It overlies the sequence of komatiites with a sharp contact, which is usually marked by a thin, grey shale unit. The top of the succession is not exposed on BOORABBIN. The clastic rocks are now soft, pale clay-rich rocks, and much genetic interpretation has to be based on field observation rather than thin-sections. The intrusive rocks are harder and better exposed than the clastic rocks. It is apparent in many of the larger breakaways that local faulting and pervasive minor folding complicate the apparent thickness.

The base of this sequence is marked by a 0.5–2 m thick grey-shale bed that is overlain by felsic volcaniclastic rock (*As*) or tuff breccia (*Aft*). Northwest of Larkinville, thin beds of conglomerate that contain pebbles of mafic and ultramafic as well as felsic rock occur at the base of the sequence. The finer-grained rocks are generally thinly bedded (1–30 cm), purple or grey to white rocks. Beds are laterally extensive; grain size ranges from mudstone to medium-grained sandstone. Coarser-grained beds range to several metres thick and are less extensive. Individual beds may be homogeneous and

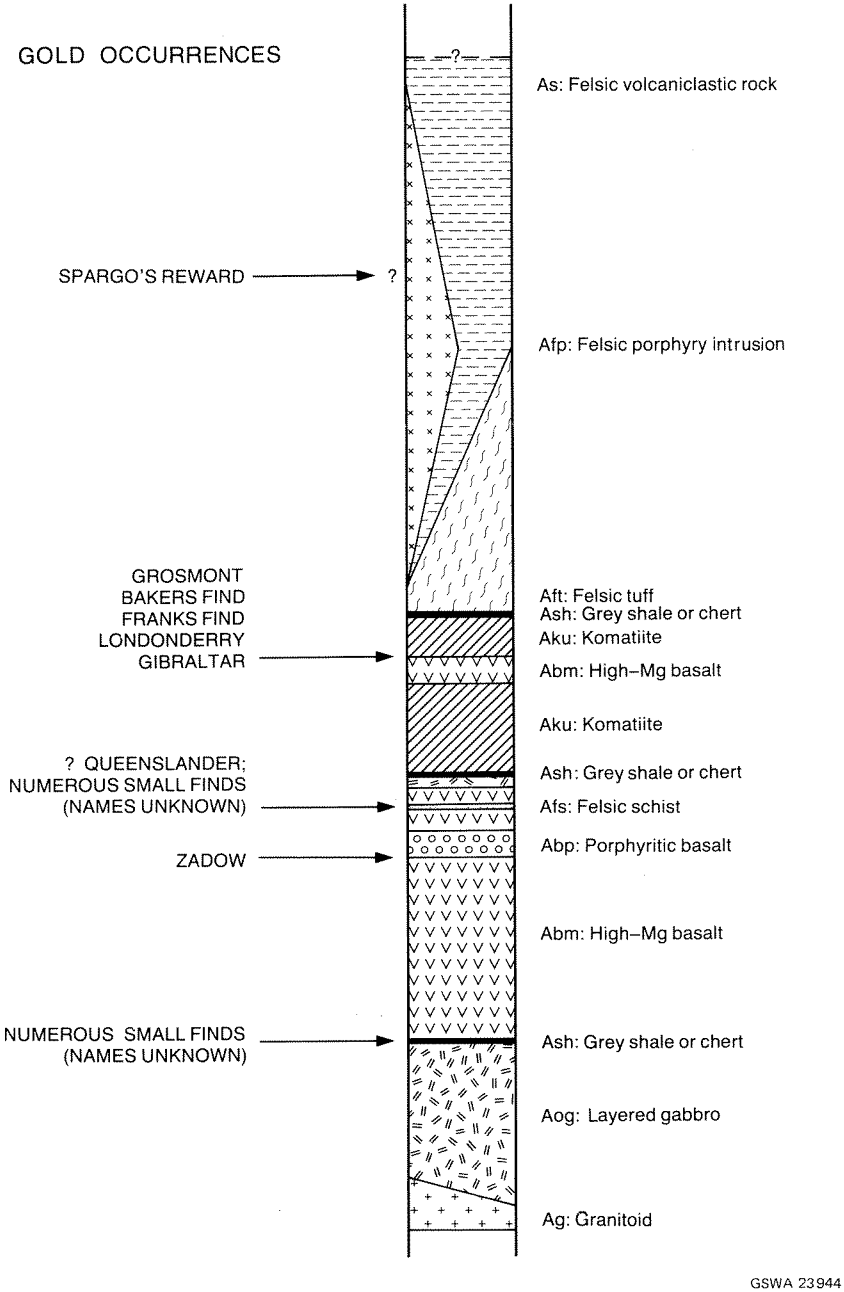


**Figure 4. Proposed stratigraphic succession with locations of gold mines**

featureless; however, graded beds and loading structures are abundant throughout, and small-scale cross-stratification is present sporadically.

The felsic volcaniclastic rock (*As*) is dominantly ash-flow tuff, in which proportions of lithic and vitric-crystal components vary both along and across strike. Epiclastic sediments are interbedded throughout the sequence, but occur in varying proportions that increase with distance from the occurrences of coarse pyroclastics and intrusives.

Accretion-lapilli occur in thick (5–10 cm) bands scattered throughout the sequence. These small (<5 mm), pale, rounded structures, which often show concentric textural or compositional variations, are embedded in fine-grained tuff. The boundaries between the lapilli and the matrix are nebulous.

Sedimentary structures, such as graded bedding, flame structures and drop-stone loading, are abundant in these rocks. Current structures, such as cross-bedding and ripple laminations, are sporadic and confined to finer-grained ?epiclastic sediments.

Grey shale units, up to 2 m thick and usually very extensive, are present within the volcaniclastic sequence; however it is uncertain whether these are primary fine-ash deposits, chemical sediments, or secondary epiclastic sediments.

At the base of the tuff unit (*Aft*) is a series of tuff breccias in which poorly sorted sub-angular cognate blocks up to 50 cm are supported by a rhyodacitic matrix of crystal-lithic tuff. All clasts have steep northerly elongation and some rounding; however, angular or swallow-tail terminations are common. The concentration and size of quartz or feldspar phenocrysts, and of biotite, varies within clasts. Ovoid clasts composed entirely of biotite, and those of basalt or dolerite, are scarce.

The matrix is a medium-grained leucocratic to mesocratic rock which has a variably granular texture, and carries up to 50% small (3 x 1 cm) ovoid lapilli (lithic clasts). Variation in mafic mineral content and orientation defines a banding which is paralleled by elongation of clasts. Localized streaky banding accompanying a microcrystalline texture indicates at least some devitrification of the vitric-crystal tuff. Wrapping of matrix textures around larger clasts is common. This has been interpreted at Spargoville (Fehlberg and Giles, 1984) as having resulted from compaction or moderate welding of ash-flow tuff, although some tectonic exaggeration of this is also evident.

Marked reduction in clast size occurs along and across strike. Crystal tuffs dominate the facies transition and comprise thinly bedded, fine- to medium-grained rocks with prominent subhedral quartz or feldspar phenocrysts.

Felsic volcaniclastic rocks (*As, Aft*) are composed of variably comminuted fragments of porphyritic dacite to rhyodacite set in a matrix of lithic, crystal, and glassy fragments. Quartz and oligoclase, and lesser amounts of microcline occur as euhedral to subhedral phenocrysts. A generally microcrystalline granular, quartzo-feldspathic groundmass carries biotite and accessory apatite, sphene, zircon and opaques. Metamorphism ranging from mid-greenschist to lower amphibolite facies has variably recrystallized both groundmass and phenocrysts, and produced minor amounts of biotite, chlorite, sericite and epidote.

In summary, this unit contains a variety of felsic volcaniclastic and intrusive rocks. The former range from proximal tuff breccias through more distal tuffs to interbedded tuffs and sediments. The complex outcrop distribution is in part facies related and in part structurally controlled. The concentration of proximal-facies volcaniclastics and intrusives in the Spargoville and east Saddle Hills areas indicates their proximity to volcanic centres and thus their potential for mineralization.

## Felsic schist (*Afs*)

Schistose felsic rocks (*Afs*) occur throughout the succession but usually in association with the grey-shale beds between basalt and komatiite flows. They are mainly thin (<1–2 m) units which may reach 5–10 m in thickness locally. Most schists are concordant and may occur in a suite of thin parallel layers or as single homogeneous units.

The felsic schist has a variably microgranular matrix composed of quartz and feldspar elongated parallel to biotite and white mica. Amphibole is present in some samples. Relict subhedral phenocrysts of plagioclase and quartz form augen set in matrix with a wrap-around texture.

The schists are similar in composition to the suite of felsic volcanic and volcaniclastic rocks, and are considered to be metamorphosed and/or tectonized products of them. Discordant varieties are clearly derived from intrusive porphyries, but concordant varieties are more difficult to assign. It is inferred, therefore, that the latter may have been derived from a variety of felsic volcanic and volcaniclastic rocks.

## Gabbro (*Aog*)

A thick (500–800 m) layered gabbro sill (*Aog*) occurs throughout BOORABBIN; it intrudes lower portions of the sequence of high-Mg basalts. The sill is never prominently transgressive except in the Saddle Hills and Karramindie belts, where sharp transgressions are evident. The upper contact is concordant but it is commonly interleaved with screens of basalt or interflow shale. The lower margin is more variable and is poorly exposed.

The gabbro contains graded layers ranging from melanocratic pyroxenite to leucocratic (quartzo-) feldspathic horizons containing scattered bladed pyroxenes. Some variation in grain size is also seen within the leucogabbro. Repetition of the compositional layering occurs on a broad scale, and two or three cycles are common. This appears to be due to magmatic processes (i.e. multiple injection of magma or double-diffusion), but intense shearing between layers at some localities indicates that some tectonic repetition occurs. Coarse subophitic to ophitic textures are preserved.

The gabbro shows heterogeneous strain; deformation was confined mainly to <2 m wide zones of amphibole schists located at the boundaries between layers. In zones of tight folding (e.g. east of Burbanks siding) there has been a general, but heterogeneous, development of foliation, which has resulted in a streaky amphibolite with broadly anastomosing schistosity of varying intensity. There are vertical and lateral textural variations from ophitic to doleritic, and original platy pyroxenes are replaced by single or matted amphibole crystals forming a strong, upright lineation.

Actinolite–hornblende pseudomorphs of pyroxene plates occur as single, randomly oriented crystals. Granoblastic recrystallization of plagioclase has produced coarse mosaics of andesine with polygonal to interlobate form; however, these are confined within the bladed form of the protocrysts. Other minerals present include quartz, chlorite, clinozoisite, magnetite, sphene, apatite, and secondary biotite.

Late deformation has had a variable effect on the gabbro, which ranges from minor strain to spaced zones of high strain or shear. Minor strain appears as patchy or wavy extinction within platy amphiboles, slight rotation of those plates, and some new growth of amphibole. In contrast, major strain is seen as strong rotation of amphibole plates and recrystallization of single plates to a mass of small spindle-shaped crystals with similar but discordant (sweeping) optic orientations. Strong rotation during later deformation was particularly prevalent southwest of Karramindie, where it is attributed to tightening and shearing of the refold against the major north–south shear marginal to the Depot Granodiorite (*Agd*).

The boundary of the gabbro sill against basalt is marked by a grey-shale layer which in many places is several metres thick. The physical contrast between the enclosing basalt and these interflow sediments provided a favourable setting for intrusion of the gabbroid magma.

Accompanying the grey shales there are commonly one or more thin layers of felsic schist, which were derived from intrusive porphyry or volcaniclastics; locally there are abundant quartz veins. This combination of features is invariably auriferous. Thermal metamorphism of the shale by the gabbro has produced a typical pelitic assemblage dominated by millimetre-sized andalusite euhedra.

Six kilometres southwest of Londonderry, the thickest continuous exposure of gabbro is truncated by a complex, interleaved granitoid margin. Over several hundred metres the western margin becomes progressively dominated by sub-parallel sheeted veins and dykes of microgranite, pegmatite, and quartz.

Along the western margin of the Nepean belt, the gabbro is truncated by granitoid, or covered by superficial deposits. On the eastern side of this belt, the sill overlies a 2–3 m thick layer of grey shale and felsic porphyry which define the closure of an open syncline. The lower margin of the sill is slightly discordant, and ocellar and pillowed high-Mg basalts form a thick screen along its southern margin. It is not clear at this locality whether this represents a true succession or whether the shale is the locus for thrusting of gabbro over basalt.

Central to the Saddle Hills belt, a similar sill has a discordant outcrop pattern and an apparent thickness of 2 km. Near Mount Herbert it lies between komatiite and felsic volcaniclastics. There are complex boundary relationships which indicate that some relationships between units may result from tectonic interleaving rather than discordant intrusion.

Gabbro also forms small sills several metres thick, and of limited extent, within the basalt pile. However, one minor sill is regionally persistent, and intrudes the boundary between high-Mg basalt and komatiite. This sill is texturally distinct from doleritic horizons which are common throughout the basalt pile. It has a strongly mottled appearance caused by single-crystal amphibole pseudomorphs of large (<5 mm), equant, pyroxene plates. The size and abundance of feldspar is variable; locally, feldspar is abundant and is coarse, relative to pyroxene, this gives the rock a weakly porphyritic appearance.

On the eastern margin of BOORABBIN, and close to the Celebration dyke, there is a large (300 x 200 m) body of layered gabbro. It is ovoid, and elongate parallel to the enclosing porphyry body, but embayed at its ends. To the west, the gabbro is coarse, very melanocratic, and its boundary with the felsic porphyry (*Afp*) is sharp. To the east, the gabbro is locally very leucocratic and medium to fine grained, and its boundary with the porphyry is sinuous. Compositional layering lies at 30° to, but is cut by, the regional north-northwest foliation. It is composed of thin bands of anorthosite and of pyroxenite containing streaky pyroxenitic augen enclosed by plagioclase. Veins of fine-grained porphyry permeate the boundary between mafic and felsic layers in the gabbro.

Microscopic and mesoscopic details indicate that this gabbro consolidated prior to its incorporation as a "raft" in the felsic porphyry magma, however its protolith is unknown.

## Felsic porphyry (*Afp*)

Intrusive felsic porphyry (*Afp*) occurs in small sub-concordant bodies throughout the BOORABBIN succession but is particularly common within the felsic-volcaniclastic pile. Good examples can be seen in the vicinity of Spargoville and along the eastern margin of the Saddle Hills.

A large (8 x 2 km), composite felsic intrusive body intrudes medium to coarse tuff breccias (to the west) and fine tuffs and sediments (to the east), 5 km northeast of Mount Herbert. There is a heterogeneous marginal zone 100–200 m wide and rich in xenoliths, and a central zone containing two relatively homogeneous porphyry types, which are distinguishable by the relative abundance of phenocrysts and the grain size of the matrix.

The western porphyry has a purple-pink, very fine-grained matrix containing abundant subhedral phenocrysts (<5 mm) of feldspar and quartz, fine flakes of biotite, and scattered, small rounded xenoliths rich in biotite. The eastern porphyry has a grey cryptocrystalline matrix carrying abundant subhedral phenocrysts of feldspar (<1 cm) and quartz (<1.5 cm, embayed); fine, oriented biotite flakes; and scattered sub-angular to rounded xenoliths of very fine-grained, biotite-rich rock.

The heterogeneous marginal zones comprise a strongly foliated porphyry matrix with 1–10 m bands of abundant xenoliths of texturally distinct porphyry and tuff breccia. Porphyry- and biotite-rich xenoliths form augen or schlieren whose attenuated "tails" merge with the matrix in a mild wrap-around texture. Feldspar phenocrysts have a random orientation.

The two porphyries are compositionally identical dacite to rhyodacite. Oligoclase phenocrysts and embayed quartz subhedra show some metamorphic recrystallization, particularly granulation around margins. The quartzo-feldspathic matrix has a microgranular texture and carries common euhedral to subhedral brown biotite and green tourmaline. Minor phases include apatite and muscovite. There is strong carbonate alteration; widespread sericitization of feldspar accompanies veinlets of carbonate and small amounts of pyrite.

The felsic porphyries are similar in composition to the volcaniclastic rocks they intrude and are therefore interpreted as consanguineous. They represent the exposed roots of a volcanic edifice mantled by its extrusive products; the two intrusions were batches of the same magma. The heterogeneous zones were produced by consecutive episodes of stoping of the tuffs and porphyries by younger intrusions; later deformation exaggerated the igneous foliation.

## Other felsic intrusions

A felsic rock type that is difficult to interpret forms two parallel outcrops 4 km southwest of Spargos Reward. The rock is a hornblende-bearing feldspar-phyric dacite whose primary foliation is produced by mineral orientation and grain-size variation. Textural and mesoscopic evidence is insufficient to classify this as a crystal tuff or a subvolcanic intrusive porphyry; both such types are common east of this locality.

SOUTHWEST BOORABBIN

To the southwest of Cat Camp (southwest BOORABBIN) a north-northwest-trending group of supracrustal rocks occurs as scattered outcrops and abundant small float fragments within low, undulating laterite-capped hills. Deep weathering and soil cover are extensive, but good evidence of the general geology is provided by comprehensive drilling and trenching by nickel-exploration companies.

The lithological association, and details of individual units, are similar to those at Coolgardie; however, only minor intrusions of dolerite (* Edyb*) were seen within the basalt (*Abm*). The felsic–clastic unit (*As*) is thicker and less deformed, and is composed of grey shales, fine tuffs, and possible epiclastic sediments.

If the structural style is equated to that on the east of BOORABBIN, then the stratigraphic sequence correlates also, namely, komatiite (*Aku*) overlying a thick basalt sequence containing an horizon of felsic clastic rocks (see Fig. 4). The western komatiite occupies a syncline which has been attenuated by axial-planar shearing. The eastern margin, close to the felsic–clastic unit, is also strongly sheared. The central region of the belt has more open, southerly plunging folds.

## Queen Victoria Rock

Four kilometres southwest of Queen Victoria Rock there is a 7 x 2 km belt of fairly well-exposed greenstones, within gently undulating hills. Data and samples from comprehensive drilling by nickel-exploration companies allows good correlation of units both along and across strike. This northwest-striking sequence has a moderate southwest dip and normal younging. Cross-faulting in an east–west direction, and intrusions of Proterozoic dykes, have produced a locally sinuous outcrop pattern. The greenstone inlier is surrounded and intruded by two major granitoids: Burra Monzogranite (*Agph*) and Woolgangie Monzogranite (*Agr*).

In general terms, there is a concordant sequence of three units: a basaltic amphibolite (*Abm*), an iron-formation (*Aci*), and a felsic–clastic sequence (*As*). A thick, locally branching, ultramafic unit lies subconcordantly to the east of the iron-formation.

The amphibolites are fine-grained, schistose, hornblende-rich rocks with, locally, distinct compositional lamination suggestive of a para-amphibolite origin. These laminae tend to be virtually monomineralic, and inequigranular blades of hornblende form textures ranging from decussate to nematoblastic. Metabasalts have an assemblage of hornblende, plagioclase, quartz, opaque minerals and sparse, colourless garnet. Bladed to equant hornblende totally replaces pyroxene, and plagioclase is very clear and untwinned. Opaque minerals, particularly as rods and blebs, appear to be associated with the amphibolitization of pyroxene. Original textures have been overprinted, and only rare occurrences of sub-poikilitic plates of hornblende suggest relict igneous texture. A granoblastic texture is now common, with straight or curved margins and 120° triple points, which indicates that a high degree of equilibrium was achieved.

Iron-formation comprises persistent, finely laminated (<2 mm) alternations of quartz-rich and iron-rich layers. Quartzose layers are white to colourless and massive to granular. Iron-rich layers are red-brown to black and moderately to strongly magnetic. Load structures and shallow current structures indicate a southwest younging to beds that dip about 45°. Restricted development of chevron and more complex folding is attributed to cross-faulting. Drill cuttings of an intersection of iron-formation at depth indicate a high metamorphic grade. Clinopyroxene dominates, but small amounts of plagioclase and bands rich in opaque iron-rich minerals are present. Associated with the opaque minerals are minor amounts of a low-birefringence mica (probably colourless chlorite) and dark spinel. Pyroxene forms either equant interlocking plates, or plates with granoblastic tracts derived from the reduction in grain size of relict subpoikilitic plates (particularly at margins). The metamorphic textures again indicate that a high degree of equilibrium was achieved.

The felsic clastic rocks are fine- to medium-grained, gritty, kaolin-rich rocks which have been re-silicified. There is a variety of well-preserved sedimentary structures, and sub-rounded quartz grains, which suggest an epiclastic origin. However, streaky feldspathic and micaceous textures, as well as lithic fragmental textures, suggest also that there are some distinct crystal and lithic tuffs present. These rocks form moderately dipping beds, younging to the southwest.

The ultramafic unit (*Aku*) in the main body of the inlier appears as a yellow-brown silicified dunite. Euhedral to subhedral olivine (<3 mm) shows well-developed cumulate textures with a massive, serpentinous intercumulus phase. No spinifex textures were observed here; however, in drill holes to the southeast and west they are common. In thin section the cumulate olivines are totally replaced by ropy-textured serpentine and bowlingite; the intercumulus phase is replaced by matted serpentine and bowlingite. There are scattered grains of rounded, or occasionally skeletal, opaque minerals. Patches of quench-textured material within the cumulate comprise fine, acicular olivine in plumose aggregates. These may be relics of the upper portion of a komatiite flow, or transported flakes from a chilled margin of a flow or intrusion. One thin section with peridotitic affinity contains large olivine euhedra, and clusters of small euhedra—some corroded—set in a pyroxene matrix. The large, interlocking pyroxene plates are now totally uralitized.

The slightly discordant and branching shape of the body, combined with the presence of cumulate textures, led exploration companies and Marston (1984) to classify this ultramafic as an intrusive dunite. However, it is evident that there has been much layer-parallel slicing, accompanying repetition of units, and crustal shortening. Together with the presence of spinifex textures nearby (and relics in thin section), these features indicate that the ultramafic unit may represent one or more tectonically modified komatiites with the cumulate zone (or zones) preferentially preserved.

## Prince of Wales

To the east and southeast of the Prince of Wales mine, a circular inlier of greenstones, 4 km in diameter, is surrounded by granitoids (*Agph* and *Agpw*). The lithologies present are similar to those of the southern Coolgardie area. Gabbro (*Ao*) and basalt (*Abm*) contain actinolite, hornblende and plagioclase, and have a strong foliation. Deformed pillows and ocelli textures are common in the basalt, while compositional layering and poikilitic textures are preserved in the gabbro. Komatiite (*Aku*) shows tremolitic spinifex textures and talc–carbonate cumulate textures. Felsic clastic rocks (*As*) show both epiclastic and pyroclastic textures.

The inlier lies 18 km along strike from the Queen Victoria Rock greenstones and has stratigraphic similarities to them. Between these two localities are several outcrops of similar supracrustal rocks; these outcrops can be associated through continuity of detailed aeromagnetics. The inference is, therefore, that the Prince of Wales inlier was laterally continuous with that at Queen Victoria Rock.

The reasons for the shape of this inlier are equivocal. The arcuate form, in granitic terrain, may be indicative of doming caused by an unexposed granitoid. However, the dip of foliation is consistently inwards at steep angles. Similar shapes are seen in the greenstones of the Coolgardie area and in granitoids of southeast BOORABBIN, and may be attributed to fold-interference patterns and/or onset of shearing. Another possibility is that of meteorite impact, for which the orientation of bedding is consistent. Small (1–2 m) impact craters which disrupt the laterite have been found in the vicinity by the author. However, no evidence was found within the inlier of impact-related textures or structures.

### Other inliers

Several isolated remnants of greenstone sequences on BOORABBIN are located by their aeromagnetic signatures. Some greenstones were intersected during nickel-exploration drilling. A strong, narrow magnetic anomaly extends 5 km southeastward from the outcrop limit of the Queen Victoria Rock inlier. At this locality, drilling revealed komatiite (*Aku*) and minor amounts of banded iron-formation (BIF). This anomaly continues in diminished form, curving from southeast to south, to a point 17 km southwest of Cave Hill. There, fine-grained, hornblende-rich amphibolites (*Abm*) and folded, finely banded BIF (*Aci*) outcrop against Burra Monzogranite (*Agph*). A similar amphibolite (*Ab*) occurs as an enclave within granitoid (*Agph*) 4 km southwest of Cave Hill.

A broad magnetic high occurs 25 km west of Queen Victoria Rock; drilling shows it to be due to komatiite and banded iron-formation. There is a tenuous link in the aeromagnetic pattern between these two greenstone occurrences, but no outcrops or relevant detailed drilling to confirm this.

In the southwest of BOORABBIN, aeromagnetic evidence, scattered outcrops, and limited drilling results show that the Cat Camp belt of greenstones continues towards the northwest, and turns north at the major north–south drainage line. Thirty-one kilometres north-northwest of Cat Camp, west of the trunk drainage, the anomaly appears to fold to the east.

## ARCHAEAN GRANITOIDS

Granitoids occupy more than 80% of BOORABBIN but have previously received scant attention: their outcrop is scattered and their economic potential was considered small. In the first edition of BOORABBIN, Sofoulis and Bock (1963) divided the granitoids into "Internal Granites" (within greenstone belts) and "External Granites" (between greenstone belts), largely on the basis of photo-interpretation. They suggested that most granitoids were gneiss and that the ovoid shape delineated by the Boorabbin palaeoriver (Fig. 1) represents a dome. Williams (1974c) summarized the geology of the granitoid rocks of the Eastern Goldfields Province.

Bettenay (1977) subdivided the granitoids of a vast tract of the southeast Yilgarn Block from LAKE JOHNSTON to LEONORA. On BOORABBIN he defined a tract of gneiss bordering the major greenstone belts, a few isolated gneiss and migmatite areas, an elongate batholith of porphyritic granitoid (from Sunday Soak to Prince of Wales), and a broad tract of "heterogeneous terrain" (western two-thirds of BOORABBIN). Geochemical differences were found only between the "external" granitoids and "internal" granitoids. On the basis of structure and petrography, Bettenay (1977) adopted a "kinematic" scheme of nomenclature relating the type of granitoid to the deformation history of the greenstone belts. Further, he held the unsubstantiated view that all country lacking outcrop is composed of gneiss and that the outcropping granitoids intrude it.

Isotopic ages have been determined from several isolated outcrops of granitoids on BOORABBIN, and are summarized in Table 1. The ages have a narrow range, suggesting that most of the granitoids were intruded within a short period or were pervasively overprinted by metamorphism.

All the granitoids on BOORABBIN are metamorphosed, but igneous rock names, after Streckeisen (1976), are used where protoliths of the granitoids can be recognized. The kinematic classification of Bettenay (1977) is not used as it was found to be of limited value. Two early granitoids are recognized at Depot Hill and Karramindie Soak, and three major and one minor occurrences of granitoids occur between the greenstone belts; a summary of the sequence of granitoid intrusion and deformation is given in Figure 3.

Granitoid rocks outcrop mainly on southeastern BOORABBIN, where there has been deeper erosion associated with a more active Cainozoic drainage system. Much of central and western BOORABBIN is covered by extensive sandplain, which overlies granitoid present at shallow depths.

Interpretation of the granitoids is hampered by paucity of outcrop. It is often difficult to determine whether one is viewing discrete granitoid bodies, rafts of older units, or younger dykes.

**TABLE 1. RADIOMETRIC AGE DETERMINATIONS, EASTERN GOLDFIELDS**

| *Age* | *Method* | *Locality* | *Reference* |
|---|---|---|---|
| **YILGARN DYKES** | | | |
| 2043 ± 40 Ma | K–Ar | Queen Victoria Rock | (a) |
| 2420 ± 30 Ma | Rb–Sr | Celebration and Jimberlana Dykes | (b) |
| **GRANITOIDS** | | | |
| **(Within greenstone belts—synkinematic)** | | | |
| 2550 ± 25 Ma | Rb–Sr | Karramindie | (b) |
| 2705 ± 35 Ma | Pb–Pb | Karramindie | (c) |
| 2585 ± 35 Ma | Rb–Sr | Mungari | (b) |
| 2640 ± 35 Ma | Pb–Pb | Mungari | (c) |
| **(Between greenstone belts—postkinematic)** | | | |
| 2600–2690 Ma | Rb–Sr | Coolgardie | (d) |
| 2632 ± 28 Ma | Pb–Pb | Lake Johnston (*Agph*) | (c) |
| **GNEISS** | | | |
| 2600–2690 Ma | Rb–Sr | Coolgardie | (d) |
| 2780 ± 60 Ma | Rb–Sr | Connolly Siding (*An*) | (e) |
| 2800 ± 100 Ma | Sm–Nd | Connolly Siding (*An*) | (e) |

(a) CSIRO (1976) (b) Turek (1966) (c) Oversby (1975) (d) Turek and Compston (1971)
(e) McCulloch et al. (1983)

## GRANITOID GNEISS (*An*)

Banded orthogneiss (*An*) occurs in apparently discrete, arcuate bodies southeast of Nepean and southwest of Sunday Soak, and also as xenoliths at the margins of Woolgangie and Burra Monzogranites. Persistent bimodal banding is dominant, and comprises biotite-rich and quartzo-feldspathic components. The biotite-rich bands, which range in thickness from one to several centimetres, are medium grained. The bands are homogeneous, except for small feldspathic clots which may have been phenocrysts, and the biotite grains lie parallel to the banding. There are pinch-and-swell structures and local discordant orientations, but generally the bands lie in subparallel bundles.

Thin aplite, pegmatite and quartz veins, of various orientations, intruded the banded gneiss prior to deformation. Where veins were originally at a low angle to banding, they have been rotated close to sub-parallel to banding to produce a finer, dispersed component of dark and light banding within dark bands, or pale, biotite-free stringers within light bands. Where veins were at a high angle to banding, deformation has produced harmonic to disharmonic folds. Thin, biotite-rich reaction rims occur along the margins of some larger feldspathic veins. Some biotite-rich stringers which cut the banding are relics of mafic dykes.

In quartzo-feldspathic bands, quartz, feldspar and minor amounts of biotite have a preferred elongation which creates a streaky augen texture. Scattered feldspathic augen within these bands indicate that the protolith may have been porphyritic. The streaky gneissosity is generally subparallel to compositional banding, but it is in some places discordant. For example, south of Sunday Soak, acute intersections between streaky gneissosity and dark biotitic bands were noted, whereas west of Connolly Siding the dark bands cut chevron folds in the streaky gneiss.

Several phases of pegmatite, some aplitic, postdate the deformation that produced the banded gneiss; they were emplaced sub-parallel to the banding.

Most of the banded gneiss is granodiorite or monzogranite in composition, but a small amount is tonalite. Field and petrographic relations indicate that the important components were a leucogneiss and a younger mesocratic granitoid. These have been mapped as individual granitoids in the southeast of BOORABBIN, under the names streaky gneiss (*Anst*) and porphyritic biotite mesocratic gneiss (*Anm*).

An early stage in the development of banded gneiss is preserved in a lakeside outcrop 17 km southwest of Sunday Soak. There, spaced, but parallel, mesocratic dykes cut leucogneiss. The dykes are strongly foliated, biotite-rich granitoid and are affected by minor folding. Early pegmatites intruded longitudinal splits in the dykes and produced a primary banding. Faint banding was also produced in the leucogneiss by pegmatite veining prior to deformation. This association of lithologies, when deformed, would produce the kind of heterogeneous banded gneiss described as banded gneiss (*An*). The latest phase, at this locality, is a granular non-foliated granitoid, similar to Woolgangie Monzogranite (*Agr*), which is partly concordant and partly discordant to the orientation of banding.

None of these granitoids has been observed to have intruded the greenstones or to be in contact with them. There is no evidence to demonstrate when formation of banded gneiss took place relative to deformation of the greenstone belts.

## STREAKY GNEISS (*Anst*)

Medium- to coarse-grained, leucocratic granitoid gneiss (*Anst*) occurs only in a few outcrops in the east and southeast of BOORABBIN. Scattered biotite forms a weak to moderate foliation parallel to streaked-out feldspars and quartz augen; this foliation is locally folded. Blebby quartz is abundant, and is elongated parallel to the biotite foliation. Locally it forms large irregular grains enclosing feldspar.

The streaky gneiss is a biotite-bearing, oligoclase granodiorite with a texture that is allotriomorphic, granular, and weakly seriate. Microcline is abundant only locally; so where it does occur it suggests a more monzogranitic composition. Accessories include apatite, zircon, and monazite.

## PORPHYRITIC BIOTITE GNEISS (*Anm*)

Porphyritic biotite gneiss (*Anm*) forms a single small body in the southeast of BOORABBIN, although identical rock forms a distinctive dyke suite within the younger porphyritic granitoid (*Agph*). The gneiss is medium-grained, mesocratic, and strongly foliated; it contains scattered, small feldspar phenocrysts or augen.

Petrographically it is a biotite-rich oligoclase granodiorite with an allotriomorphic, granular to gneissic texture. Subhedral to anhedral phenocrysts of plagioclase and some microcline are scattered throughout. Biotite generally makes up 30% of the rock and has a preferred orientation parallel to the walls of the intrusion. The quartzo-feldspathic matrix generally shows some recrystallization. Accessories include magnetite, apatite, zircon, and zoned sphene.

## GRANITOID (*Ag*)

Where granitoid is undivided because of its complexity, limited size, or discontinuous outcrop, it is referred to as granitoid rock (*Ag*). Most rocks so designated are leucocratic, medium- to coarse-grained biotite monzogranite, in many places interlayered with pegmatite and aplite. Also included in this definition (*Ag*) are small intrusions within supracrustal belts that trend parallel to the greenstone rocks and are commonly deformed with them. In a few places dense swarms of granitoid (*Ag*) sheets occupy up to 50% of the greenstone outcrop.

## WOOLGANGIE MONZOGRANITE (*Agr*)

Although texturally distinct, this recrystallized granular granitoid (*Agr*) is compositionally indistinguishable from Burra Monzogranite. It occurs in discrete homogeneous outcrops, as well-defined dykes in other granitoids, and as stoping veins near margins of Burra Monzogranite. Such intrusive relationships are well displayed around Queen Victoria Rock. Bodies of this granitoid occur mainly along valleys and other lineaments parallell to the foliated margin of Burra Monzogranite. Southeast of Nepean, and southwest of Sunday Soak, arcuate trends of Woolgangie Monzogranite are associated with occurrences of granitoid gneiss (*An*). Woolgangie Monzogranite is typically coarse-grained, granoblastic, and lacks foliation. It contains a few relict feldspar phenocrysts; these are corroded, subhedral to anhedral grains only slightly larger than the groundmass, with zoning marked by inclusions.

The unit (*Agr*) is a biotite monzogranite. Its texture is allotriomorphic, seriate to equigranular. Perthitic microcline occurs as small, scattered phenocrysts with poikiloblastic margins. Oligoclase is zoned and its crystals tend to be more anhedral than subhedral. Complex resorption and replacement reactions are evident between plagioclase and both quartz and microcline. Quartz is strained, and partly recrystallized to elongate domains of subgrains; there are also coarse irregular patches of quartz enclosing plagioclase islands and peninsulas. Biotite content is variable and accessories include apatite, zoned zircon, and allanite. Woolgangie Monzogranite is characterized petrographically by its complex intergrain boundaries, indicating recrystallization; and by vestiges of deformation such as elongation of quartz and feldspar, and the direction of fragmentation of quartz domains.

The suite of macroscopic inclusions in Woolgangie Monzogranite is similar to that found in Burra Monzogranite; however, there appears to have been a far more fluid relationship between host and inclusions. For example: mafic xenoliths are generally attenuated into zones of schlieren, and granitoid rafts are more thoroughly veined and assimilated; these reactions produce distinctly laminated zones of heterogeneity. Four groups of xenoliths occur in Woolgangie Monzogranite in narrow zones trending northwest, or sometimes north-northeast. The xenoliths, which are elongate parallel with these zones, include:

(a) Wispy trains of biotite derived from highly attenuated basic xenoliths or more mafic granitoid intrusions.

(b) Wall rock ranging from large angular to smaller rounded fragments, and schlieren of metagabbro or metabasalt which were strongly foliated, folded and veined prior to inclusion. At Boorabbin Rock, angular fragments are streaked out into trains of inclusions in continuity with biotitic clots, schlieren, and wispy banding. Clusters of mafic xenoliths are surrounded by reaction zones of coarse-grained to pegmatitic granitoid containing amphibole.

(c) Disrupted dykes of biotite granodiorite, up to 20 cm across, occur as trains of attenuated fragments. They are medium grained, mesocratic, aphyric and strongly foliated, usually with sharp biotite-rich margins. They are locally attenuated and become small biotitic clots.

(d) Nebulous inclusions of compositionally banded biotite-monzogranite gneiss, with compositions similar to the host Woolgangie Monzogranite, except for segregations of biotite into <2 cm bands.

Woolgangie Monzogranite is undeformed and all diagnostic dyke suites found in the Burra Monzogranite are cut by it.

## BURRA MONZOGRANITE (*Agph*)

Burra Monzogranite (*Agph*) makes up 55–60% of the granitoid terrain. It is characterized by prominent megascopic microcline phenocrysts, up to 3 x 1 cm in size. They are subhedral, tabular to prismatic, zoned, and, in some places, twinned. Where phenocrysts are less abundant and smaller, some have corroded margins. Where Burra Monzogranite is strongly foliated, as at Gnarlbine Rock, the matrix wraps around the phenocrysts. A very coarse-grained variety of Burra Monzogranite, with phenocrysts commonly 10 cm in length, occurs 20 km south-southeast of Cat Camp. This is a major body tens of kilometres across, rather than a pegmatitic enclave. A similar lithology was noted in northwest LAKE JOHNSTON (Gower and Bunting, 1976).

The coarse-grained granular matrix of Burra Monzogranite is mainly hypidiomorphic; it comprises quartz, oligoclase and biotite with accessory zircon, apatite and magnetite, and traces of allanite and ilmenite. Phenocrysts are dominantly microcline subhedra with variably poikilitic margins, but some plagioclase phenocrysts also occur. Quartz makes up 25% of the matrix and, in some places, forms large areas enclosing plagioclase.

Three kinds of inclusions occur within the porphyritic granitoid:

(a) Narrow biotite-rich stringers, less than 5 mm wide, are locally cut by feldspar phenocrysts of the host. Where these stringers are thin and persistent, they represent early dykes or highly attenuated xenoliths of more mafic (possibly basic) lithologies. Otherwise, they are patchy and irregular but associated with fine- to medium-grained equigranular granitoid, slightly foliated in places. The relationship indicates reaction between the host and entrained granitoid xenoliths.

(b) Irregular rafts of banded granitoid gneiss have diffuse boundaries. These rafts invariably lie with their banding and long axes subparallel to any foliation in the host rock. Apophyses of porphyritic granitoid stope subcentimetre-wide leucocratic bands, and lit-par-lit assimilation of the gneiss is apparent. A particularly good example of this can be seen 5 km north-northeast of the Prince of Wales mine.

(c) Amphibolite xenoliths occur as fragmental enclaves up to 50 cm across. Reactions between the enclaves and their host resulted in a coarser crystallization of the adjacent granitoid. Both coarse-grained amphibolite (after gabbro) and fine-grained amphibolite (after basalt) are found. The latter always shows marked foliation and folding, which were imparted prior to incorporation by the granitoid. Angular extremities of blocks degrade to trains of fragments of diminishing size. In the extreme these are recognized as trails of schlieren and biotite stringers.

The Burra Monzogranite is so voluminous that it is probably not a simple monolithic unit; rather, it may comprise many separate and probably sheet-like intrusions, which have been folded. To support this interpretation, relevant lithological features are detailed below.

Variations occur in the size, shape, and abundance of microcline phenocrysts; there are also subtle variations in texture of the groundmass. While these features alone might indicate inhomogeneity in a single magma, they may be taken with other evidence to suggest multiple plutons. In specific zones, Burra Monzogranite exhibits a foliation that is produced by mineral orientation within the matrix, as well as by alignment of phenocrysts. The zones of foliation are narrow but continuous; they increase in intensity towards the margins of the pluton. There is no apparent lineation.

Deformation of granitoid dykes in these marginal zones indicates that there was compression perpendicular to the pluton margins and minimal extension or shear. The forms delineated by these zones are interpreted as individual plutons, of unknown thickness, which vary from rounded to oblate and are elongate towards 150°. Notable exceptions are zones of foliation which parallel linear features such as major drainage channels and photo-lineaments; these features are attributed to concealed, large faults. Similar zones also occur within the Burra Monzogranite at the margins of greenstone belts, such as in the Cat Camp and Queen Victoria Rock areas.

The suite of inclusions described above occurs within the same northwest–southeast zones as the foliated facies of the host rock, this suggests their source was original wall rocks. There is some cross-cutting evidence that indicates a long and complex intrusive history for Burra Monzogranite. Intrusion of the Burra Monzogranite appears to both predate and postdate greenstone deformation, and a mesocratic dyke suite both predates and postdates its marginal foliation.

VARIANTS OF BURRA MONZOGRANITE

## Bullabulling Monzogranite (*Agb*)

The Bullabulling Monzogranite (*Agb*) outcrops between a foliated margin of Burra Monzogranite and the western limit of the Coolgardie greenstone belt. This rock is fine to medium grained, and contains subhedral microcline phenocrysts up to 5 mm long. The phenocrysts are tabular to equant, twinned, and have ragged edges. A weak, shallow, southerly dipping fabric is marked by feldspar phenocrysts and biotite. Mafic xenolithic clots are abundant, but dispersed. They vary in shape from ovoid to rectangular or linear; the constituent biotite is massive to laminated. Angular xenoliths of foliated amphibolite, up to 1 m, occur along the eastern margin of the pluton. Fluorite is also abundant.

Bullabulling Monzogranite is similar in composition to Burra Monzogranite, in that it has a quartz–biotite–oligoclase–microcline matrix and microcline phenocrysts. However, the matrix is seriate granoblastic with a partly interlobate to polygonal texture. Both quartz and feldspar are strained, and myrmekite occurs in blebs. Accessory minerals include fluorite and metamict monazite.

The Bullabulling Monzogranite appears to be a finer grained enclave of Burra Monzogranite which intruded prior to the intrusion of the Gnarlbine–Prince of Wales pluton (*Agpw*). The latter has magmatic contacts with metasediments and metabasalts but has been deformed later along with them.

## Magnetite-rich monzogranite (*Ago*)

To the west of Bullabulling, a small granitoid body (*Ago*), intrudes metasedimentary rocks. It is characterized by abundant 2–3 mm euhedra or subhedra of magnetite, dark flecks of chlorite of similar size, and sparse phenocrysts of feldspar. It is a foliated, medium- to coarse-grained muscovite–biotite–oligoclase monzogranite with identical textures to the Bullabulling Monzogranite (*Agb*). Accessory minerals are abundant, and include metamict monazite, magnetite and apatite. Its juxtaposition with the Bullabulling Monzogranite, and its similar texture and composition, suggest that it is a contaminated variety of that rock.

## Augen monzogranite (*Aga*)

In the northwest corner of BOORABBIN, from Koorarawalyee northwards, there are large but scattered outcrops of an augen granitoid (*Aga*). The granitoid contains large microcline euhedra in a very strongly foliated, mesocratic matrix. The feldspar crystals are rotated and are partly rhomboid. Biotite forms weak, streaky segregations which are parallel to quartzo-feldspathic stringers. In thin section, the augen granitoid has an allotriomorphic, granoblastic texture. The granodiorite matrix contains oligoclase and abundant, rarely twinned, orthoclase; there is accessory apatite. The rocks are thoroughly recrystallized and exhibit curved crystal margins.

Macroscopic textural contrasts, and mafic stringers, indicate that there was strong attenuation of early granitoid dykes and basic schlieren. However, later dykes show evidence of cross-cutting, which indicates multiple deformation. Two dyke suites are dominant—a biotite-rich porphyritic variety up to 1 m in width, and a leucocratic biotite-bearing variety generally 5 m in width (possibly Woolgangie Monzogranite).

Both suites appear to cut an early foliation; however, there are frequent small offsets in the dykes oriented subparallel to foliation in the host. The dykes are also crossed by a weak foliation parallel to the foliation in augen granitoid.

The lithological associations, and cross-cutting relationships of dykes are similar to those seen in Burra Monzogranite. The augen granitoid is therefore interpreted as a highly deformed variety of Burra Monzogranite. Field evidence indicates an increase in deformation from east to west towards a large north–south drainage, while regional aeromagnetic patterns and satellite imagery reveal a major dextral shear along the line of this drainage which extends into JACKSON and BARLEE. It can be concluded that the marginal processes described for Burra Monzogranite (*Agph*) also occurred here to produce a foliated, inclusion- and dyke-rich pluton margin. This was subsequently the locus for coaxial deformation which further compressed the foliated monzogranite to produce the augen texture, an overprinting recrystallization, and a foliation in the late dykes.

## PRINCE OF WALES GRANODIORITE (*Agpw*)

West of the Prince of Wales gold mine, there is a small (10 x 2 km), poorly exposed body of granitoid (*Agpw*) which trends in a north-northwesterly direction. The rock is a coarse-grained, strongly foliated, hornblende–biotite granodiorite with evidence of a complex recrystallization history. Foliation, marked by prismatic bundles of biotite and abundant lensoid biotitic xenoliths (5–10 x 2 cm), is not parallel to the elongation of the outcrop but appears tangential to the arcuate greenstones to the east. Such a disposition may indicate a relationship between these two features in the form of a concealed dome; however, dips of foliation in the greenstones are consistently inward. The orientation of foliation in the granodiorite parallels major photolineaments to the southwest, which are interpreted as faults.

In thin section, its texture is granoblastic to gneissic seriate; crystals range from hypidiomorphic through interlobate to polygonal. Green hornblende is poikiloblastic, but is locally replaced by large crystals of brown biotite. Calcic oligoclase is the dominant feldspar but scattered subhedral microcline is also present. Accessory minerals include zircon, apatite, magnetite, and sphene.

## DEPOT GRANODIORITE (*Agd*)

The Depot Granodiorite (*Agd*) is an ovoid (10 x 20 km) body, elongated parallel to the trend of the adjacent greenstones observed in the Depot Hill and Horse Rocks area. In the north the Depot Granodiorite is abruptly truncated by the Celebration Dyke and by a fault parallel to Change Creek, whereas its poorly exposed southern margin appears to interfinger with greenstones in the Spargoville area. Metasedimentary rocks are stoped by the granodiorite on its western side; relics of garnet and cordierite indicate a narrow contact aureole. Some deformation occurred parallel to a major shear which cuts the boundary between metasedimentary rocks and other greenstones to the west. The eastern contact of the granodiorite is also sheared against metasedimentary rocks and greenstones. Near the northeastern margin of the pluton there are a number of minor dextral shears up to 30 cm wide which trend northeast and form *en echelon* sets related to the two bounding regional shears. A strong foliation with low to moderate dip is apparent around the margins for several hundreds of metres but no lineation was detected; the foliation is cut by pegmatite dykes up to 2 m wide.

Depot Granodiorite is medium to coarse grained, and has scattered, rounded relict feldspar phenocrysts in a streaky granular matrix. It is hornblende-bearing leuco-granodiorite to leuco-tonalite, with polygonal to interlobate granoblastic texture. Hornblende (<10%) is generally porphyroblastic and is associated locally with green clinopyroxene. Plagioclase is dominantly oligoclase with thin albitic rims and patches, apparently products of partial melting. Quartz exhibits a mild gneissose fabric. Small amounts of epidote, apatite, and allanite are present. The presence of metamorphic hornblende and clinopyroxene indicates that the granodiorite has experienced a metamorphic event at middle to upper amphibolite facies.

Archibald and Bettenay (1977) considered that this granitoid was emplaced as a solid-state diapir, and they associated dynamic metamorphism with such an event. However, there is clear evidence that the pluton was emplaced magmatically and that some stoping margins were subsequently modified by shearing. The shears, which are not confined to the vicinity of the pluton but extend for tens of kilometres north and south, appear to wrap around it. This indicates that shearing occurred late in the deformation of the greenstones and that the granitoid acted as a competent core around which the more ductile greenstones were deformed. Strain was concentrated around the margin of this core.

## KARRAMINDIE MONZOGRANITE (*Agk*)

Karramindie Monzogranite (*Agk*) forms a few small outcrops which define a subcircular area of about 7 $km^2$. This subcircular structure truncates the trend of the adjacent greenstones, but no contact is exposed. The monzogranite is leucocratic, fine to medium grained, and homogeneous, except for sparse ovoid biotite clots. It is not foliated, but a weak, subhorizontal mineral alignment is seen in the northwest of the body and is parallel to a major fault system immediately to the southwest. Pegmatite veins a few millimetres wide intrude a spaced network of fractures.

This unit (*Agk*) is a biotite monzogranite containing <6% red-brown biotite, and minor secondary muscovite and chlorite. Oligoclase and K-feldspar occur in equal proportions as zoned laths, most of which are strained. The texture is granoblastic, seriate and interlobate, but locally polygonal; this suggests that the granitoid has undergone metamorphism at middle- to upper-amphibolite facies.

Such a conclusion raises problems of the timing of emplacement of Karramindie Monzogranite. Its discordant form and lack of foliation indicate that the intrusion post-dated maximum deformation, and hence maximum metamorphism, of the adjacent greenstones. Bettenay (1977) included this K-rich granitoid in his suite of "fractionated leuco-adamellites" which have distinctive trace-element patterns. The granitoid has been the subject of a number of isotopic-age determinations, which are presented in Table 1. Chemical similarities between Karramindie and Mungari (southeast KALGOORLIE) granitoids led Oversby (1975) to speculate on their being "separated outcrops of a single intrusion continuous at depth". However, the lead-isotopic systematics indicate significantly different ages of intrusion, the Mungari pluton being younger.

## PEGMATITE (*Agp*)

Pegmatite (*Agp*) occurs throughout BOORABBIN as veins, patches, or large tabular discordant bodies. It was emplaced at various times, and ranges in nature from deformed veins in orthogneiss to undeformed bodies in greenstone belts and granitoids. Its main constituents are quartz, microcline and albite, and various amounts of biotite. Larger bodies tend to be compositionally zoned parallel to their walls. Graphic intergrowths of quartz and feldspar are widespread.

Within the granitoids, pegmatites consist mainly of quartz, feldspar and minor amounts of mica; whereas in the greenstones they commonly contain a suite of exotic minerals. Minerals which have been commercially extracted from these pegmatites include: feldspar, biotite, tantalite, and beryl; lithium-bearing feldspar (petalite), pyroxene (spodumene), mica (zinnwaldite, lepidolite), and tourmaline (rubellite); and red-brown garnet. Details of the important pegmatites and their mineralogy are given in the economic geology section of these notes.

Thermal aureoles occur around some of the pegmatites and range from narrow (<1 m at Mt Marion) to broad (12 m at Londonderry). Alteration of wall rock was hydrothermal and the wall rocks generally contain biotite and tourmaline; an exotic amphibole, holmquistite, occurs at Mt Marion (Wilkins et al., 1970).

The origin of these pegmatites is unknown as they are relatively small and isolated. Ross (1964) cited the nearby Depot Granodiorite as a probable source of the pegmatite at Mt Marion. He correlated this with a similar deposit at Ravensthorpe (Ross, 1964) and with the observations of Rowe (1954) on the occurrence of lithium pegmatites in Canada. However, since the BOORABBIN pegmatites are undeformed and strongly discordant to lithological and structural trends, they must have been emplaced at a late stage, which by inference post-dates the Depot Granodiorite.

Field relations imply that the larger BOORABBIN pegmatites are probably related to the later stage fractionated granitoids such as the Karramindie Monzogranite. A petrogenetic grid for lithium-rich pegmatites, proposed by London (1984), establishes that "under the quartz-saturated conditions that prevail in pegmatites, stability relations among the Li-aluminosilicates are a function of pressure and temperature and are largely independent of the nature and proportions of other phases". Using this grid in a qualitative sense, it can be deduced that pegmatites at Londonderry were emplaced at a lower crustal level (by about 2 kb) than those at Mt Marion.

## GRANITOID DYKES

A suite of dykes cut the granitoids; their cross-cutting relationships have been used to establish relative ages of dykes and host plutons. Dykes are most abundant in the foliated, xenolith-rich marginal zones of plutons.

The most abundant dykes are of fine- to medium-grained mesocratic, biotite-rich granodiorite with macroscopic and microscopic similarities to porphyritic biotite gneiss (*Anm*). Scattered subhedral to anhedral microcline phenocrysts occur; in deformed dykes these become streaked out to augen. Biotite is unevenly distributed across larger dykes and streaky bands rich in biotite parallel dyke margins. The bands form swirls and folds around irregularities in dyke walls; these features indicate an igneous origin.

These dykes are not seen in Woolgangie Monzogranite but are abundant in the foliated margins of Burra Monzogranite. There were apparently diachronous relationships between dyke intrusion and foliation development throughout BOORABBIN. Some of these dykes were intruded at low to moderate angles to the pluton margin prior to solidification of the magma and to marginal deformation. They occur as sinuous, pinched or disrupted dykes generally less than 0.5 m across. Metamorphic biotite and re-oriented phenocrysts or augen are parallel to host foliation, and have similar orientations. This structure is well displayed at Gnarlbine Rock, and indicates that the dykes were deformed together with Burra Monzogranite by compression perpendicular to the pluton margin. Where dykes were at low angles to the margin, offsets were produced as a precursor to rotation into parallelism with foliation, whereas those at moderate to large angles generated harmonic to disharmonic folds.

In undeformed parts of Burra Monzogranite plutons, some dykes occur as rounded fragments. The morphology and presence of mutual veining suggest that these dykes were intruded before consolidation of the plutons. Younger dykes cut those in the foliated margins of the plutons. They range from parallel-sided competent dykes, intruded after consolidation, to pinch-and-swell dykes intruded late in the consolidation process (e.g. southwest of Prince of Wales). The apparent diachronous relationship between intrusion of these dykes and the development of foliation at the margins of Burra Monzogranite is taken, in part, as evidence for the existence of discrete plutons of Burra Monzogranite which had slightly different intrusion and/or cooling times.

Moderately abundant dykes of biotite monzogranite cut Burra Monzogranite but are never found in Woolgangie Monzogranite. The dykes are usually parallel-walled straight dykes with sharp margins. They are not foliated and have an equigranular texture, microscopically identical to Woolgangie Monzogranite. These monzogranite dykes may be apophyses of the major granitoid Woolgangie Monzogranite.

The youngest group of granitoid dykes are aplites 20–50 cm wide that have saccharoidal texture and minor amounts of biotite. They have sharp, parallel-sided contacts in Burra Monzogranite, but in a few places in Woolgangie Monzogranite they show pinch-and-swell structures. Therefore, the aplite appears to be related to the intrusion of Woolgangie Monzogranite and may represent a late-stage, volatile-poor component of that magma.

## STRATIGRAPHY

The greenstones of BOORABBIN lie towards the western margin of the broad Norseman–Wiluna greenstone belt. Throughout this belt there is a limited but discontinuous group of lithologies. Correlation of similar lithologies is hampered by poor exposure and structural complexity. Where surface or subsurface exposure is adequate, local stratigraphic successions have been erected, but correlation between them, along or across strike, is difficult. Even within local successions, critical boundaries may be concealed or tectonized.

Previous mapping on BOORABBIN has provided the basis for several stratigraphic interpretations, e.g. McMath et al. (1953), Sofoulis and Bock (1963), and Gemuts and Theron (1975). Each described a thick succession in which lithotypes were repeated throughout, and some authors evoked cycles of volcanic activity (e.g. Williams, 1969, 1971).

A local stratigraphic succession is now proposed, based on the regional geology presented in this revision of BOORABBIN and in detailed studies of the same area (Hunter, in prep.). The succession is simple, but it has been complicated by multiple events of folding and faulting, and punctuated by stages of granitoid intrusion. The succession is best seen in the Burbanks–Grosmont area. Here, exposure is reasonable and refolding moderately open with relatively minor tectonic attenuation. However, eastwards from Burbanks–Grosmont, complex occlusion and repetition of portions of the succession are produced by progressively tighter refolding, and pervasive slicing and shearing.

A summary of the succession is given in Figure 4. A thick sequence of basalts, mainly high-Mg, is the lowermost unit. This contains thin horizons of basaltic tuff, interflow sediments and feldspar-phyric basalt, and is intruded by gabbro. Komatiite, containing thin layers of interflow sediments and one of basalt, overlies the high-Mg basalts. The top of the succession on BOORABBIN consists of an heterogeneous sequence of felsic volcaniclastic rocks, flows, intrusions, and minor sediments.

## STRUCTURE

### GREENSTONES

Previous structural interpretations on BOORABBIN envisaged thick complex sequences being folded into isoclines, which were modified by faulting and cross-folding (McMath et al., 1953; Sofoulis and Bock, 1963; Gemuts and Theron, 1975). A detailed discussion of the structural history of the region west of Kalgoorlie is given by Hunter (in prep.) while a summary is given below for that portion comprising BOORABBIN.

Deformed greenstones may be divided into two domains in which different tectonic aspects predominate. From Karramindie to Wannaway, linear greenstone trends comprise mafic–ultramafic anticlinoria and felsic synclinoria; there has been a complex history of longitudinal attenuation and interleaving through pervasive shearing and compression. From Gibraltar to Burbanks the greenstone belts are arcuate, and both synclinoria and anticlinoria are within the mafic–ultramafic portion of the succession. Here, a similar complex history of deformation has been experienced; however, the more open style is due to the structural influence of three granitoid bodies and the development of confined shear zones.

The earliest deformation ($D_1$) is inferred to have been recumbent folding, possibly accompanied by thrusting, which generated a layer-parallel fabric ($S_1$). Regional compression in a northeast–southwest direction ($D_2$) produced open to tight, locally overturned folds with northwesterly axes. Intrusion of the main "internal" granitoids occurred at this time, probably through partial melting below descending keel zones.

The succeeding deformation ($D_3$) was a complex northwest to southeast crustal shortening. It produced crenulation, and either folding and/or wrench faulting, depending on the prior relationship of the greenstones to the granitoids. In the Grosmont–Burbanks–Londonderry area, and at Hampton Locality 59, greenstones were folded between competent granitoid masses. These "refolds" are characterized by a sinuous, open to tight form, and northeast-trending axes.

Along eastern BOORABBIN development of shear zones was predominant with consequent slicing of the succession. From Karramindie through Logans Find to Wannaway, there is marked interjection and lensing of lithologies, which is attributed to development of broad zones of anastomosing, spaced shears in the Kunanalling Shear Zone (Hunter, in prep.). The Mungari Shear Zone (Hunter, in prep.) can be traced from the Saddle Hills to Larkinville as a narrow (10–20 m) schist or mylonite unit, which has sinistral offset.

Renewed northeast–southwest regional compression produced tightening of earlier north-northwest-trending structures and "wrap-around" of structures adjacent to competent granitoid masses (such as the Depot Granodiorite). Cleavage ($S_4$) is distinguishable at the hinge zones of refolds and in the Londonderry–Burbanks belt, but it is otherwise parallel to $S_1$. Foliation and reverse faulting at granitoid margins (e.g. Depot Granodiorite) may be associated in part with this event. A dextral shear zone, extending north from Nepean, and past Londonderry and Burbanks gold mines, may be related to $D_4$ or antithetic to $D_3$.

A fault swarm, perpendicular to all greenstone belts, represents a phase of rigid-block adjustments following the major deformation event, or events, of $D_4$. In the Karramindie to Wannaway belt these faults have acted as conduits for the Widgiemooltha dykes (*Ɇdy*).

## GRANITOIDS

Granitoids within greenstone belts have had a complex history of intrusion and deformation. Stoping margins and contact metamorphic aureoles are discordant to, and therefore postdate, the layer-parallel $S_1$ foliation; thus magmatic intrusion during $D_2$ is inferred. Deformation is confined to narrow marginal zones where non-lineated foliation is parallel to the pluton margins. Interiors of the plutons are structurally isotropic and structural elements of host greenstones wrap around each. It is deduced that, after consolidation of the granitoids, $D_3$ deformation imparted a marginal foliation to the competent granitoid masses. During subsequent $D_4$ compression, the more ductile greenstones were deformed around relatively rigid granitoids.

Relative ages of intrusion of granitoids between greenstone belts can be deduced from field observations (Fig. 3), but there is no direct evidence to relate their timing to deformation events within the greenstones. It is suggested that streaky gneiss (*Anst*) and porphyritic biotite gneiss (*Anm*) may represent a pre-greenstone sialic basement. Field evidence suggests that banded granitoid gneiss (*An*) was produced by deformation of such a basement. Radiometric age determinations (e.g. McCulloch et al., 1983) indicate that this took place at about the time of extrusion of the supracrustals, and may, therefore, be related to $D_1$. The arcuate trends of gneiss outcrops are attributed to macroscopic fold-interference patterns.

The later major granitoids (*Agph* and *Agr*) have clear magmatic intrusive contacts with their precursors. Foliated and inclusion-rich facies form annular zones confined to the margins of apparent plutons, but the interiors are homogeneous. Foliations are vertical and have no mineral lineation. It is proposed that such features in the Burra Monzogranite (*Agph*) indicate emplacement by "ballooning tectonics" (Ramsay, 1981; Wikstrom, 1984). The monzogranite was probably intruded in sheeted form into the gneissic basement. Woolgangie Monzogranite (*Agr*) intruded parallel to the margins of Burra Monzogranite (*Agph*) and, as a result, inherited some of its heterogeneities. Regional compression (?$D_2$ or ?$D_4$) folded the sheeted complex about northwest–southeast axes to produce the present orientations.

A major dextral shear zone, trending north-northeast, cuts the northwest corner of BOORABBIN. Deformation associated with movement on it produced augen monzogranite (*Aga*) from Burra Monzogranite (*Agph*). Parallel to the shear zone is a swarm of faults which offset the trends of *Agph* and *Agr*, and in some places cut the greenstone belts. This event is tentatively correlated with $D_4$ of the greenstones structural history.

## LINEAMENTS

Lineaments are widespread and evenly distributed on BOORABBIN; three classes are distinguished, and orientations of discrete segments were measured on each 1:50 000 map sheet. The data were plotted as rose-diagrams, with a ten degree class interval, and radii as percentages of the population (Fig. 5).

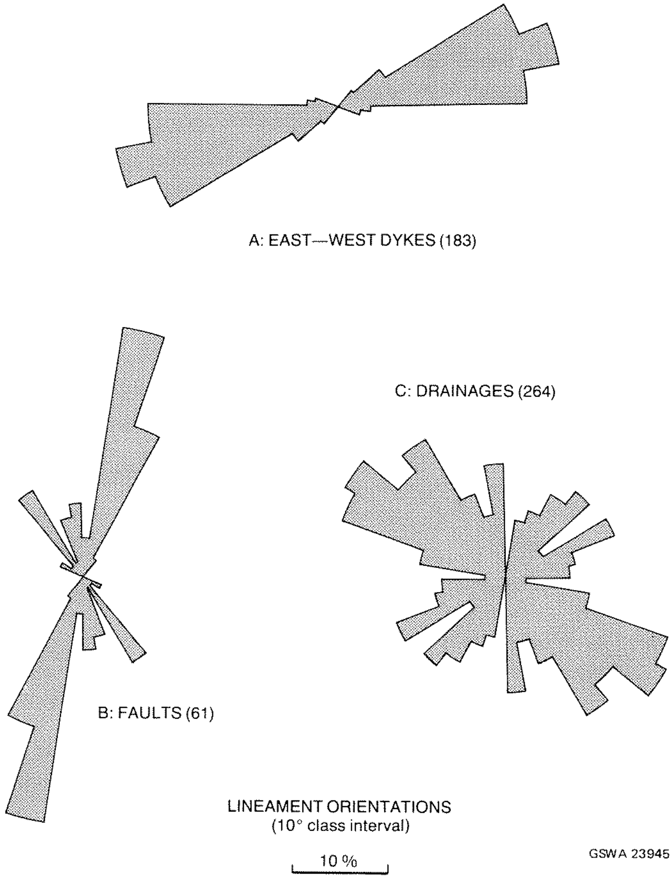


**Figure 5. Rose diagrams of lineaments**

## Dykes

All features considered to be related to the Widgiemooltha dyke swarm, such as sandplain lineaments, faults in greenstones (known from drilling or magnetic data to carry dykes), and outcropping dykes themselves, are recorded together as *Edy*. Figure 5A shows a strongly bipolar distribution with little variance about a mean of 75°. In detail, however, this can be subdivided into three main orientations of 70°, 80°, and 90°. Radiometric age determinations on these and similar dykes in the Yilgarn, together with magnetic data, indicate a protracted history of dyke injection. There is some evidence on BOORABBIN that orientation of dykes is related to the period of injection.

## Faults

Faults occur predominantly within the granitoid terrain, and are distinguished from the dykes by their narrowness. They can be traced for tens of kilometres on BOORABBIN, and, using Landsat imagery, on sheets to the north and south. Some of the larger, stronger lineaments appear as narrow, negative anomalies on regional aeromagnetic compilations.

There is a dominant bipolar orientation (Fig. 5B) to the north-northeast, and two minor bipolar orientations to the north-northwest and northwest, each with little variance. These correspond to mapped and inferred offsets in lithological trends which are interpreted as faults. The dominant orientation is that of the most persistent faults which can be traced into the greenstone belts as shear zones (e.g. at Coolgardie).

### Drainages

The strong linearity of most drainage elements suggests that basement geology determines their courses. Course directions were measured throughout the granitoid terrain of BOORABBIN and in some of the larger drainages within the greenstone belts.

The resulting rose-diagram, Figure 5C, shows a complex distribution of orientations, which suggest contributions from a variety of basement features. The dominant orientation lies, with broad variance, between north-northwest and west-northwest. Lesser, but discrete, orientations lying to the north-northeast and north are attributed to control by faults. Those lying east- northeast parallel the Widgiemooltha dyke swarm. If contributions from faults and dykes are removed from the data then a strong northwest to west-northwest orientation remains. This corresponds to the trend of zones of strong foliation and heterogeneity at the margins of the main granitoid types, *Agph* and *Agr*.

## PROTEROZOIC DYKES

Two sets of dykes (*Ᵽdy*) with a generally east–west trend occur throughout BOORABBIN, but they are best exposed within the greenstone belts and the more dissected portions of the granitic terrain, as in the southeast. Where dykes are concealed they can be recognized by characteristic subparallel photolineaments or distinctive, discordant aeromagnetic signatures. They have a maximum width of 400 m (Binneringie Dyke [*Ᵽdyb*]) but are generally less than 200 m wide. The dykes are discontinuous and have small primary offsets and bifurcations, within 10–20 km strike length; the dykes are subvertical and have sharp margins.

Exceptions to the general east–west trend occur 2 km southwest of Mt Marion, where a two kilometre section of the Celebration Dyke (*Ᵽdyc*) is deflected into the northwesterly greenstone trend; and 9 km north-northeast of Sunday Soak where a 10 km long dyke within streaky gneiss (*Anst*) trends north-northwesterly, parallel to the Wannaway greenstone belt.

The dykes may be divided into two groups based on orientation (see Figure 5A) and polarity, but no cross-cutting relationships have been observed in the field.

Little work has been published about the dykes of BOORABBIN, but detailed studies have been made of prominent members of the suite on neighbouring sheets. Sofoulis (1966) introduced the term "Widgiemooltha Dyke Suite" for the generally east–west dykes of the Eastern Goldfields. For consistency with other groupings of dykes in Western Australia, these dykes are referred to as the Widgiemooltha dyke swarm (Myers, 1990).

Samples from the Celebration and Jimberlana Dykes have given a Rb–Sr age of 2420 ± 30 Ma (Turek, 1966). However, isotopic analyses of dykes from Kambalda (Roddick, 1974) and Queen Victoria Rock (CSIRO, 1976) give Rb–Sr ages of 2085 ± 17 Ma and 2043 ± 40 Ma respectively.

The largest dyke of the Widgiemooltha dyke swarm is the Binneringie Dyke (* Edyb*), which crosses southeast BOORABBIN from Sunday Soak to the greenstones southeast of Cat Camp. It is 585 km long and has a maximum width of 3.2 km (on WIDGIEMOOLTHA). McCall and Peers (1971) made a detailed study of the field relationships, petrography, and chemistry of the eastern part of this dyke. Another large dyke of this suite, the Jimberlana intrusion, is 180 km long and up to 2.5 km wide. It lies south of BOORABBIN but is the most studied dyke of this suite. It has a funnel-shaped cross-section and an internal lopolithic structure of layered cumulates (Campbell, 1966, 1968, 1987). It has been compared with the Great Dyke of Rhodesia by Campbell et al. (1970). Its economic potential for nickel and copper was discussed by Travis (1975).

Detailed aeromagnetic data from the Eastern Goldfields identifies both positively and negatively polarized dykes. West-southwest trending dykes are positive, and the most abundant; east–west dykes are negative. Palaeomagnetic studies by Evans (1968) suggest that the magnetic orientations are consistent regardless of the polarity of the dyke.

On BOORABBIN the dykes have sharp contacts, thin (<5 cm) chilled margins, and coarse-grained gabbroic centres. They are homogeneous and carry rare mesoscopic felsic xenoliths, except for a locality near Sunday Soak where the Binneringie Dyke shows vertical compositional banding (McCall and Peers, 1971) and contains felsic dykes and xenoliths.

Most dykes are orthopyroxene gabbros, but a few are olivine gabbros containing up to 10% olivine. Large platy augite is fresh, but smaller grains of orthopyroxene are altered and commonly rimmed by hornblende. Labradorite forms an intercumulus phase (locally sericitized) with accessory opaques and apatite. Plagioclase adjacent to quartz is zoned from andesine cores to oligoclase rims. Quartz makes up 5% of the rock, and occurs as symplectic or micrographic intergrowths with plagioclase. Mafic minerals are altered locally to amphibole, chlorite, and biotite. This may reflect either late-stage igneous reactions or contamination by assimilated granitic country rock, with the quartz as xenocrysts.

McCall and Peers (1971) describe a variety of granophyric enclaves within the dykes and regard them as differentiated portions of the basic magma. However, there is widespread evidence on BOORABBIN of thermal metamorphism of granitoids occurring up to 4 m from dyke walls, and advanced partial melting within one metre. Although no examples of back-veining were seen during the present survey, conditions were evidently suitable for this to occur. It is proposed, therefore, that the quartzo-feldspathic "xenocrysts" and granophyric enclaves and veinlets are the products of magma contamination by stoped fragments and rheomorphic back-veins derived from the granitoid country rock.

## CAINOZOIC GEOLOGY

Cainozoic units form an extensive cover over the Precambrian rocks on BOORABBIN. A summary of Cainozoic geology appears on the map sheet (in pocket); Figure 6 shows a schematic section of Cainozoic unit relationships. They were delineated by detailed air-photo interpretation of surface morphology, lithological associations, floral communities, and by representative field inspections. Some units are diachronous; others, particularly the poorly consolidated units, have been, or are being, reworked. The author therefore favours broader temporal labels rather than the narrower ones given, for example, by Kriewaldt (1969).

### CAINOZOIC UNITS

Immediately overlying deeply weathered Archaean basement rocks are remains of a lateritic duricrust (*Czl*). Outcrops are confined to the tops of breakaway scarps and their eroded back-slopes. The laterite unit (*Czl*) comprises: brown to yellow-brown limonitic pisoliths cemented by subvitreous ferro-siliceous cement; friable rubble associated with degraded substrate; reworked products of these, particularly veneers of haematitic granules in dark-red gritty soil; and siliceous laterite products overlying ultramafic rocks. The latter, commonly known as "cap rock", are brown to white varieties of amorphous, cherty silica such as chalcedony, agate, jasper, and cellular quartz.

Laterite grades upward into a sandplain (*Czs*) of yellow to white, generally mature, quartz sand, with traces of iron oxides. Limonite pisoliths are abundant in the sand, particularly near the base above laterite (*Czl*). The association of sandplain with laterite suggests it formed as a deeply leached fossil soil (Carroll, 1939). However, it is evident that the unit has had an extended history of aeolian and fluvial reworking.

Granitic eluvium (*Czg*) may be equivalent to the precursors of sandplain (*Czs*). It consists of pale pink to yellow, coarse, gritty to loamy sands. This unit represents quartzo-feldspathic and fragmental eluvium overlying granitoid rock, and therefore

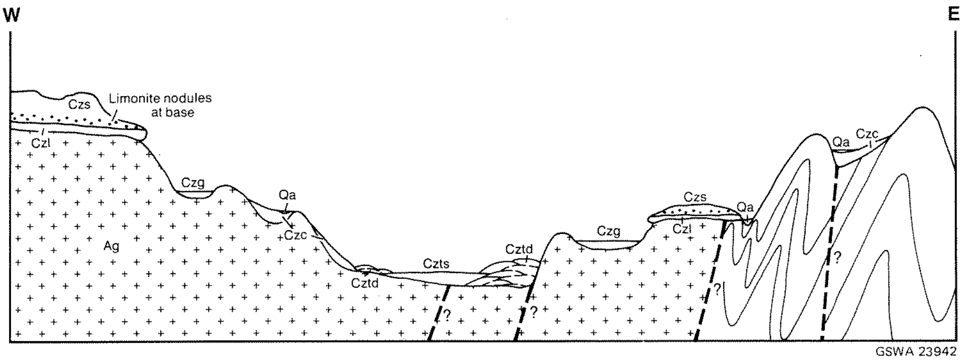


**Figure 6. Schematic section showing relationships of Cainozoic units**

appears to underlie laterite and sandplain. However, isolated patches of this unit occur on high ground within sandplain; this relationship is interpreted as due to minor reworking of granitic soils (*Czg*) at high points in the palaeotopography. Ancient reworking of the lateritic and granitic soils has produced, in low ground, flat-lying, brown to white, immature sediments, commonly called "silcrete" or "billy". They have a vitreous appearance due to a siliceous or hematitic cement. Angular quartz clasts are predominant, and range from coarse sand to sand size.

Colluvial deposits (*Czc*) are unconsolidated or poorly consolidated, and represent a variety of extant processes of erosion and deposition. These red, pink, or yellow sand to sandy loams are widespread as immature, polymictic detrital deposits forming fans and broad flood-washed plains. There is no formal channelling of material in this unit and episodic reworking is common.

Around playa lakes two major aeolian deposits (*Cztd* and *Czts*) are distinguished according to their degree of consolidation. Stabilized deposits (*Cztd*) are white to pale-yellow, powdery to gritty, granular soils. They comprise interleaved sand and gypsum which form dune and hummock ground along major trunk drainages, and are stabilized by halophytes or very open casuarina and eucalypt woodland. The most recent deposits occur on the eastern shore of the playa lakes. Non-stabilized aeolian deposits (included in *Czts*) are white dunes and banks of crystalline gypsum and salt with sand on the surface of the larger playa lakes. These may have seasonal or longer term variations in form and support only scattered halophytic vegetation.

Ephemeral saline lagoons, mainly in trunk drainages, contain lacustrine deposits rich in evaporites (*Czts*). White to grey surface layers are principally gypsum and salt with a thin crystalline salt veneer. Beneath are black to brown interbedded evaporites, muds, and sands. Near granitoid rock, and close to the watersheds on sandplain, there are perched ephemeral lagoons of fresh or brackish water. Such lacustrine deposits (included in *Czts*) are rich in red to grey muds and silt; many have thick vegetation around the margins or even on the surface.

### QUATERNARY UNITS

Alluvium (*Qa*) is confined to channels or braided river complexes, and consists of unconsolidated or poorly consolidated, immature, poorly sorted sands and gravels. This detritus is polymictic and varicoloured, and of local provenance.

## ECONOMIC GEOLOGY

Mineral production from BOORABBIN has been sporadic, despite the diversity of resources. Gold mining and exploration has the longest history, and most interest has been centred on the area south of Coolgardie, between Gibraltar and Burbanks. Large mining centres have flourished and waned, but several are now being revived as medium-tonnage, low-grade, open-cut operations. Production statistics for all commodities are given in Tables 2 and 3.

**TABLE 2. GOLD PRODUCTION FROM BOORABBIN TO 1989**

| *Mining centre; lease or producer name* | *Alluvial* (*kg*) | *Specimen and dollied* (*kg*) | *Ore treated* (*t*) | *Gold therefrom* (*kg*) | *Silver* (*kg*) |
|---|---|---|---|---|---|
| **BULLABULLING** | | | | | |
| Pool Mans Wealth (1989) | — | — | 621.00 | 3.107 | — |
| The Golden Soak (1988) | — | — | 430.00 | 1.035 | — |
| May Joy (1988) | — | — | 73.15 | 0.552 | — |
| Bernguard | — | — | 1 449.14 | 6.505 | — |
| Worked Out | — | — | 197.11 | 6.952 | — |
| Pakahas Son | — | — | 464.59 | 7.737 | — |
| Valiant Consolidated (1989) | — | — | 60 | 1.8 | — |
| J & V Dickson (1989) | — | — | 45 | 0.881 | .077 |
| Other current leases | .305 | — | 215 | 3.928 | 0.076 |
| Sundry claims (to 1985) | 0.162 | .61 | 2 279.2 | 26.944 | — |
| Voided leases (to 1975) | — | — | 3 152.59 | 44.133 | — |
| **Total** | **0.467** | **0.61** | **8 986.78** | **103.574** | **0.153** |
| **BURBANKS** | | | | | |
| Belgium Queen (1978–79) | — | — | 383.0 | 0.77 | — |
| Belgium Queen Extended (1980-81) | — | — | 595.0 | 1.08 | — |
| Brown Dog (1981) | — | — | 307.0 | 0.256 | |
| Grosmont (1974–89) | — | 1.292 | 91 602.0 | 215.54 | 5.429 |
| Grosmont North (1981–84) | — | 0.053 | 478.0 | 9.086 | |
| Grosmont South (1981–83) | — | — | 242.0 | 2.466 | — |
| Hockin, D. (1983–85) | — | — | 349.0 | 0.438 | 0.078 |
| Lady Robinson (1973–89) | — | — | 93 272.41 | 483.338 | — |
| The Gap (1983) | — | — | 287.0 | 1.926 | — |
| Colling & Sendzuik (1989) | — | — | 253.0 | 1.047 | — |
| New Lord Bobs (1968–81) | — | — | 1 021.97 | 3.17 | — |
| Susan (1980) | — | — | 1 859.00 | 3.872 | — |
| Glenloth (1977–86) | — | — | 684.0 | 2.607 | — |
| Ivanhoe | — | 0.088 | 205.24 | 3.055 | — |
| Warwick A. Taylor | — | — | 45.00 | 0.068 | — |
| Burbanks Birthday G.M. Ltd | | | 72 816.09 | 1 478.18 | |
| Lord Bobs | — | — | 3 239.52 | 100.87 | |
| Lord Bobs G.M. Syndicate | — | — | 3 549.9 | 184.09 | — |
| Burbanks–Bonnievale Prospecting Co. | — | — | 3 781.73 | 45.852 | — |
| King, A (1985–88) | — | — | 186.0 | 0.841 | 0.002 |
| Last Chance (1985) | — | — | 300.0 | 0.198 | 0.011 |
| Manchuria (1981–86) | — | — | 201.0 | 0.346 | 0.014 |
| Ivan | — | — | 177.81 | 6.871 | — |
| Main Stay | 0.048 | 0.034 | 266.20 | 3.211 | — |
| Rinaldi, L. (1984–87) | 6.369 | 0.183 | 3 638.0 | 87.141 | 4.137 |
| Royal Standard | — | — | 1 160.83 | 7.981 | — |
| Golden Arch | — | 0.316 | 524.62 | 4.97 | — |
| Other current leases | 1.759 | — | 324.0 | 1.173 | 0.009 |
| Sundry claims (to 1988) | 1.750 | 15.637 | 20 380.74 | 300.499 | 0.066 |
| Voided leases (to 1986) | 0.626 | 11.375 | 342 405.49 | 7 701.29 | 16.208 |
| **Total** | **10.552** | **28.978** | **644 535.55** | **10 652.232** | **25.954** |
| **GIBRALTAR** | | | | | |
| Reform (1978–80) | 2.851 | — | 977.00 | 1.891 | |
| Manfred Curry (1977–82) | — | — | 117.0 | 0.124 | — |
| Lloyd George (1947–89) | — | 0.608 | 3 794.65 | 18.594 | 0.427 |
| Eleventh Hour | — | — | 105.67 | 0.095 | — |
| Limerick (1988–89) | — | — | 238.00 | 1.286 | — |
| Little Beauty (1981–83) | | 0.04 | 325.0 | 0.357 | 0.004 |
| Pan Australia (1986–89) | — | — | 753 207.0 | 842.707 | — |
| Carlton | — | — | 2 364.74 | 45.486 | — |

| *Mining centre; lease or producer name* | *Alluvial (kg)* | *Specimen and dollied (kg)* | *Ore treated (t)* | *Gold therefrom (kg)* | *Silver (kg)* |
|---|---|---|---|---|---|
| **GIBRALTAR continued** | | | | | |
| Other current leases | — | — | 98.0 | 1.662 | 0.017 |
| Sundry claims (to 1984) | 0.043 | 1.579 | 4 245.37 | 46.657 | — |
| Other voided leases (to 1986) | — | 0.58 | 36 854.52 | 579.43 | 0.348 |
| **Total** | **2.894** | **2.807** | **802 326.95** | **1 538.289** | **0.796** |
| **GNARLBINE** | | | | | |
| Gold Demon (1980–82) | — | — | 375.00 | 1.170 | — |
| Emu Export (1975) | — | — | 81.00 | 0.384 | — |
| Jules Reward (1982–89) | 0.07 | 0.145 | 1 066.0 | 7.682 | 0.109 |
| Phaeton | — | — | 715.80 | 7.033 | — |
| Prince of Wales G.M. Co Ltd. | | — | 1 270.0 | 11.42 | |
| Sala (1983–84) | — | — | 220.0 | 0.497 | — |
| Great Gnarlbine | — | 0.434 | 280.16 | 17.03 | — |
| Sundry claims (to 1987) | — | 0.152 | 1 233.13 | 15.783 | 0.003 |
| Voided leases (to 1982) | — | — | 761.5 | 6.45 | — |
| **Total** | **0.07** | **0.731** | **6 002.59** | **67.449** | **0.112** |
| **LARKINVILLE** | | | | | |
| New Lark | — | — | 232.00 | 7.859 | 0.459 |
| Ground Lark | — | .822 | 2 308.51 | 100.9 | — |
| M. Henry (1988) | — | — | 120.00 | 0.618 | — |
| Spargos Reward (1989) | — | — | 9 812.0 | 67.55 | 0.418 |
| Sundry claims (to 1988) | 0.073 | 4.642 | 676.9 | 35.58 | 0.018 |
| Other voided leases (to 1980) | 0.708 | 0.87 | 64.01 | 0.39 | — |
| **Total** | **0.781** | **6.334** | **13 213.42** | **212.897** | **0.895** |
| **LOGANS FIND** | | | | | |
| Great Lion | — | — | 1 158.29 | 4.01 | — |
| Dorothy Gay (1966–67) | — | — | 98.05 | 12.78 | — |
| Spargos Reward G.M. (1935) NL | — | 0.345 | 107 089.02 | 818.78 | — |
| Frankson | — | — | 486.16 | 1.85 | — |
| Hourigan M.E. (1988) | — | — | 100.00 | 0.39 | 0.012 |
| Perseverance | — | — | 475.57 | 11.79 | — |
| Patricia Jean (1981, 1987) | — | — | 1 412.0 | 2.092 | — |
| Crescent Gold Mines | — | — | 176.03 | 1.769 | — |
| Crescent–Perseverance (1986–89) | — | — | 278.0 | 3.374 | 0.225 |
| Westmin | — | — | 109.73 | 0.284 | — |
| Other current leases | — | — | 84.0 | 0.564 | — |
| Sundry claims (to 1985) | 0.214 | 17.157 | 3 649.64 | 114.04 | 1.421 |
| Other voided leases (to 1986) | — | — | 145.8 | 3.48 | — |
| **Total** | **0.214** | **17.502** | **115 262.29** | **975.203** | **1.658** |
| **LONDONDERRY** | | | | | |
| Carnicelli, E.B. (1987–88) | — | — | 306.0 | 0.723 | — |
| Vice Regal | — | 0.059 | 4 538.47 | 59.26 | 0.011 |
| Christmas Box | — | 0.043 | 2 608.58 | 68.929 | — |
| Londonderry G.M. Ltd | — | 1.903 | 11 525.5 | 361.88 | — |
| Sundry claims (to 1973) | 0.519 | 2.512 | 4 392.28 | 83.982 | 0.697 |
| Other voided leases (to 1948) | — | .951 | 16 029.28 | 201.63 | — |
| **Total** | **0.519** | **5.468** | **39 400.11** | **776.404** | **0.708** |
| **TOTAL ALL CENTRES** | **15.497** | **62.430** | **1 629 727.69** | **14 326.048** | **30.276** |

NOTE: Leases are in the Coolgardie Mineral Field. Emphasis has been placed on recent production (years in brackets). Historic production is mostly from (now) voided leases.

**TABLE 3. PRODUCTION OF GOLD AND OTHER MINERALS REPORTED TO THE MINES DEPARTMENT TO 1989**

| *Mining Centre* | *Gold* (*kg*) | *Silver* (*kg*) | *Beryl* (*t*) | *Building stone* (*t*) | *Feldspar* (*t*) | *Petalite* (*t*) | *Columbite-tantalite* (*t*) | *Sand and gravel* (*t*) | *Nickel in concentrate* (*t*) |
|---|---|---|---|---|---|---|---|---|---|
| Bullabulling | 104.651 | 0.153 | — | — | — | — | — | — | — |
| Burbanks | 10 691.762 | 25.954 | — | — | — | — | — | 34 676 | — |
| Gibraltar | 1 543.990 | 0.796 | — | 623 | — | — | — | — | — |
| Gnarlbine | 68.250 | 0.112 | — | — | — | — | — | — | — |
| Larkinville | 220.012 | 0.895 | — | — | — | — | — | — | — |
| Logans Find | 992.919 | 1.658 | — | — | — | — | — | — | 12 578.26 |
| Londonderry | 782.391 | 0.708 | 255.05 | 164 | 74 313 | 3 041.97 | 1.45 | — | 24 774.22 |
| **Total** | **14 403.975** | **30.276** | **255.05** | **787** | **74 313** | **3 041.97** | **1.45** | **34 676** | **37 352.48** |

## GOLD

Apart from Spargos Reward, no new mining centres have been discovered on BOORABBIN since early this century; present activity is exploiting previously worked ground. Gold workings are restricted to the greenstone belts, and all, except Spargos Reward, are located within the mafic–ultramafic portion of the succession. There is correlation between the location of old mines, and the intersection of faults or shears with specific horizons in the stratigraphy proposed in this report. A schematic representation of the stratigraphy is given in Figure 4 with indications of the location of more prominent mining centres.

There are no major gold-mining operations on BOORABBIN, although several open-cut mines are exploiting medium-tonnage, low-grade deposits, and numerous small-scale underground mines are worked ephemerally. Near Bullabulling, economic concentrations of gold are being delineated within laterite overlying metasediments and amphibolites.

Recent exploration in the Gibraltar district has defined reserves and resources which warrant extraction; the open-pit at Kunanalling–Gibraltar produced 842 kg Au from 753 000 t during the last four years. At Grosmont, open-pit mining is continuing; previously stockpiled ore with an average grade of just under 3 g/t is being treated. While one open pit west of the Burbanks Town Dam has been operating periodically, extensive exploration in the region is concentrated on extensions to the mineralized Burbanks Shear. Encouraging results have been obtained from drilling at the long-abandoned "Londonderry Gold Mine". Spargos Reward Gold Mine has undergone extensive dewatering, refurbishing, and drilling; its current reserves are quoted as 100 000 t at 7.6 g/t Au down to 90 m. Production in 1989 was 9 812 t for 67.545 kg Au.

## NICKEL

During the 1960s and 1970s, ultramafic rocks of all greenstone belts, concealed and exposed, were thoroughly investigated for their nickel potential. Economic and subeconomic nickel deposits were found at the base of komatiite flows west of Londonderry, at Nepean, and south of Spargoville. Although two nickel mines were established—Nepean, and Andrews shaft (Spargoville)—both are now closed.

Concise but detailed accounts of the Nepean and Andrews shaft (Spargoville) deposits are given by Marston (1984); he includes statistics of production history and details of the mineralogy of the host and ore bodies. The Nepean mine ceased production in May 1987 when economic reserves were mined out. Total production of nickel in concentrate was 24 774.22 t. Following the downturn in the economics of nickel mining towards the end of the 1970s, Andrews shaft was closed in January 1980; the overall production of nickel concentrates was 12 578.26 t (Marston, 1984).

North and west of the Londonderry goldmine, three deposits have been outlined but not exploited (Marston, 1984). All lie at the base of a west-facing komatiite unit, in contact with either basalt or gabbro. Within a 4 km radius of Andrews shaft, three other nickel prospects have been evaluated and described by Andrews (1975). Three kilometres southwest of Queen Victoria Rock, an isolated occurrence of greenstone is bounded by granitoids. A complex ultramafic body there contains disseminated Ni-sulphides, which Marston (1984) classified with his "intrusive dunite-associated deposits".

## PEGMATITE AND RELATED MINERALS

Pegmatite bodies carrying a variety of lithium-bearing minerals have been mined southwest of Londonderry, and reserves have been delineated near Mt Marion. Many small pegmatite bodies have been mined by individuals for minerals such as tantalite–columbite and beryl.

The only major producer is the Londonderry feldspar group of quarries at the southern tip of the Grosmont–Burbanks belt; however, production has been erratic and the quarries are now idle. Production figures are included in Table 3.

In the Saddle Hills, south of Mt Marion, a number of flat-lying pegmatite bodies have intruded basalt and gabbro. Spodumene is present as pale-green prisms up to 1 m long, which assay 6.08% lithium (Tomich, 1956). There has been no production from this deposit but presently estimated reserves are 3 Mt at 1% lithium oxide.

Tantalite–columbite has been recovered from pegmatites at Londonderry, Tantalite Hill, Mt Marion, and south of Spargoville, but only in small quantities. The last-named occurrence was described by de la Hunty (1953), who included the following mineral analysis: $Nb_2O_5$ (68.5%); $Ta_2O_5$ (7.65%); $TiO_2$ (0.70%); $SnO_2$ (0.40%).

Micas of differing composition occur in all these pegmatites and at Grosmont, and have been extracted as a by-product with other commodities. Muscovite and biotite are the most common, but their lithium-bearing variants, lepidolite and zinnwaldite, are more valuable.

Cassiterite and beryl have been won from several pegmatites in small amounts. Beryl forms large crystals at Londonderry and Spargoville.

## OTHER COMMODITIES

### Sand and gypsum

The courses of palaeorivers in the Eastern Goldfields contain valuable resources of sand and gypsum, and also water. Thick deposits of yellow to white quartz sand (*Czs*) occur as sandplain overlying laterite. Sand also occurs as thick aeolian deposits on the eastern margins of playas; however, impurities such as salt and gypsum are common and dunes are of variable thickness and extent. Dunes forming at the margins of playas are locally rich in gypsum, but the resource has yet to be exploited.

## Coal and oil shale

Studies of the palaeodrainage systems in parts of Western Australia (Bunting et al., 1974; van de Graaff et al., 1977) have revealed the potential for coal and oil shale in the Cainozoic sediments which fill the playas and associated trunk drainages. Encouraging, but uneconomic, results of exploration have been recorded for the WIDGIEMOOLTHA and Norseman areas (Griffin, 1989). In the southeastern corner of BOORABBIN, a portion of the Lefroy palaeoriver was drilled in a few localities but basement was shallow. Evidence of marine incursion in this area consisted of a few occurrences of lignite, sponge spicules, and glauconite. Sediments encountered were dominantly fluvial and lacustrine. Tertiary sediments at Coolgardie, containing brown coal and carbonaceous clays, have been described by Balme and Churchill (1959).

## Semi-precious stones

Within a silicified shear zone from Spargoville to Larkinville, deposits of prase, and fuchsite and sericite in massive to flaggy rocks provide interesting decorative stone. Deposits are discontinuous and only one is known to have been worked commercially (Connolly, 1960).

Veins and sheets of opaline silica and agate are common in the weathered zone of komatiites. Unusual varieties, and well-formed examples of minerals, are common in the diverse pegmatites of BOORABBIN.

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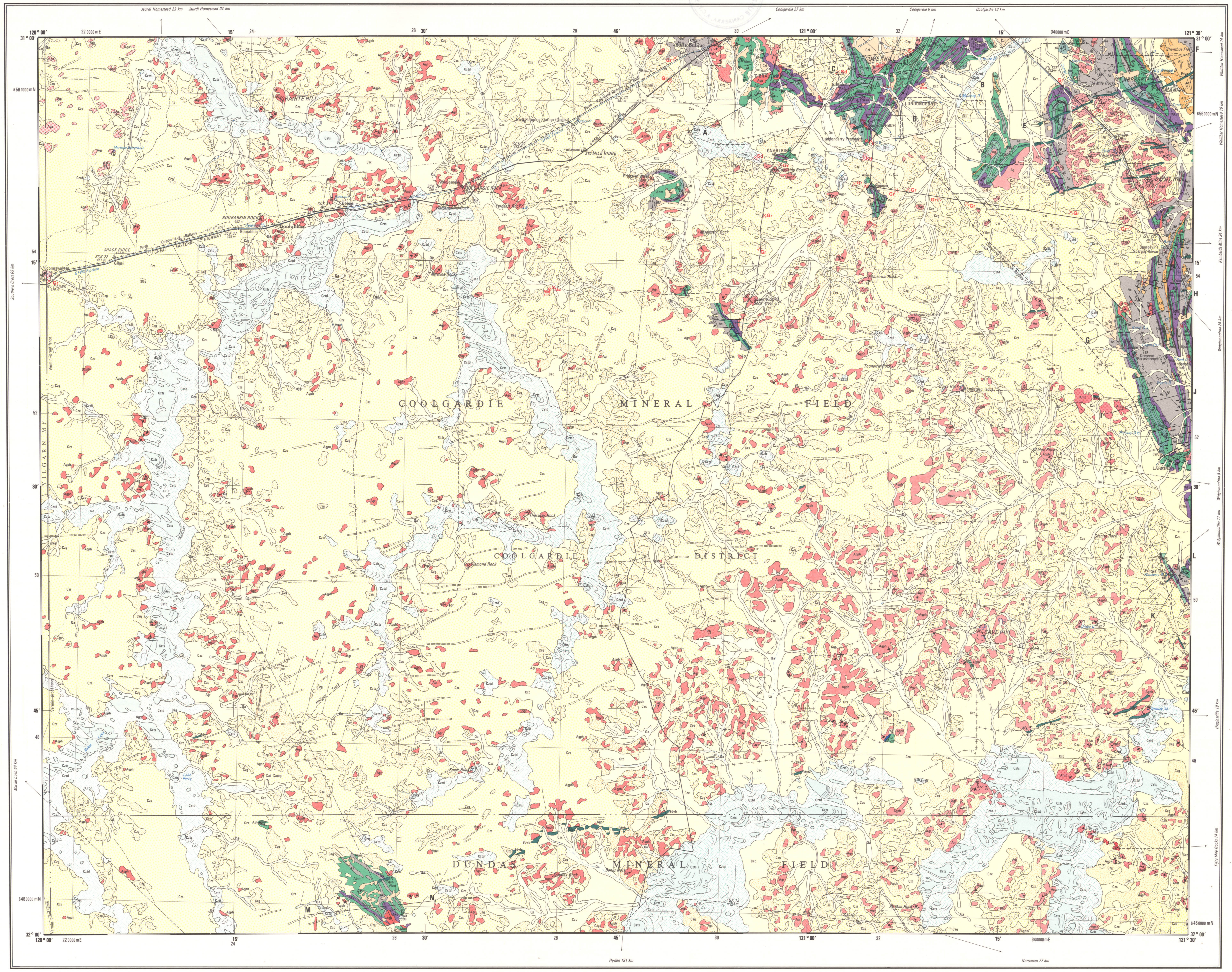
# BOORABBIN

GEOLOGICAL SURVEY OF WESTERN AUSTRALIA






Geology by : W M HUNTER 1981–84

## SYMBOLS

Geological boundary
Fault, inferred or concealed
Shear zone
Minor fold, showing plunge
Bedding
- inclined
- vertical
- horizontal

Younging indicator
- sedimentary
- graded
- igneous pillows
- differentiated intrusion

Cleavage
- inclined
- vertical

Foliation, metamorphic
- inclined
- vertical

Foliation, igneous
- inclined
- vertical

Joints
- inclined
- vertical

Lineation
Air photo lineaments
- concealed mafic dyke
- lithological or structural trend

Mineral field boundary
Highway with national route marker
Formed road
Track
Railway abandoned
Old tramway formation
Powerline
Town, pop. less than 1000 — Boorabbin
Building
Locality — Connolly
Landing ground
Microwave repeater site
Horizontal control; major, minor
Vertical control, height accurate — SCK 31 407 m
Breakaway
Sand dunes

Watercourse, ephemeral
Pipeline — P
Well — W
Windpump
Soak — Sk
Dam — D
Tank — T

Mining locality — LARKINVILLE
Mine, (gold unless otherwise indicated) — Prince of Wales
Drill hole
Down hole stratigraphy — Aku
Mineral occurrence
- gold — Au
- nickel — Ni
- pegmatite — Pg

Pit
- gravel — Gr
- rock (includes road metal and ballast) — Rk
- sand — Sd

## REFERENCE

### CAINOZOIC

QUATERNARY — Qa Alluvium

Czts Evaporite interbedded with clay and sand
Cztd Sand, silt and gypsum in stabilized dunes

Czc Colluvium
Czg Quartzo-feldspathic sand over granitoid rock
Czs Sandplain with limonitic pisoliths near base
Czl Laterite and reworked products

### PROTEROZOIC

Ᵽdy Mafic and ultramafic dykes : Ᵽdyb – Binneringie Dyke; Ᵽdyc – Celebration Dyke; Ᵽdyr – Randalls Dyke

### ARCHAEAN

Ag Granitoid rock
Agr **WOOLGANGIE MONZOGRANITE** : recrystallized monzogranite and granodiorite
Agph **BURRA MONZOGRANITE** : coarse porphyritic monzogranite
Agb **BULLABULLING MONZOGRANITE** : foliated, partly recrystallized monzogranite with scattered microcline phenocrysts
Ago Magnetite-bearing, foliated and recrystallized monzogranite
Aga Coarse augen-monzogranite
Agpw **PRINCE OF WALES GRANODIORITE** : foliated and recrystallized hornblende-biotite-granodiorite
Agd **DEPOT GRANODIORITE** : hornblende-granodiorite and tonalite with scattered microcline phenocrysts
Agk **KARRAMINDIE MONZOGRANITE** : recrystallized biotite monzogranite
Agp Pegmatite

An Banded granitoid gneiss
Anst Granodiorite and tonalite with streaky augen of quartz and granular feldspar
Anm Porphyritic granodiorite and monzogranite; biotite-rich and strongly foliated

As Pelitic and psammitic metasedimentary rocks with metaconglomerate, chert and metamorphosed felsic volcaniclastic rocks
Ash Metamorphosed grey shale with chert
Aci Metamorphosed banded iron-formation

Af Metamorphosed felsic volcanic and volcaniclastic rocks
Aft Metamorphosed dacite and rhyodacite tuffs
Afp Metamorphosed intrusive dacite porphyry

Afs Felsic schist

Ao Metamorphosed mafic and ultramafic intrusive rocks
Aog Metagabbro

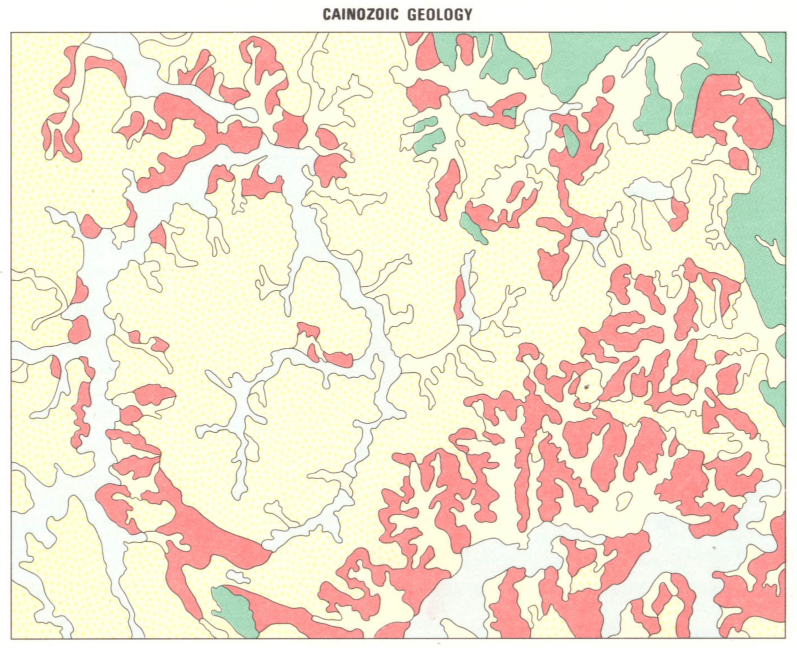
Ab Mafic schist, metabasalt, metadolerite and amphibolite
Aba Metamorphosed basaltic agglomerate
Abm Metamorphosed high–Mg basalt
Abp Metamorphosed porphyritic basalt and dolerite

Aku Metakomatiite

Au Ultramafic schist

INDEX TO 1: 250 000 SHEETS

### CAINOZOIC GEOLOGY



Scale 1: 1 000 000

Alluvium + Colluvium
Playa deposits and dunes
Sandplain over thin laterite
Granitic eluvium with outcrop
Greenstone eluvium with outcrop

SCALE 1: 250 000

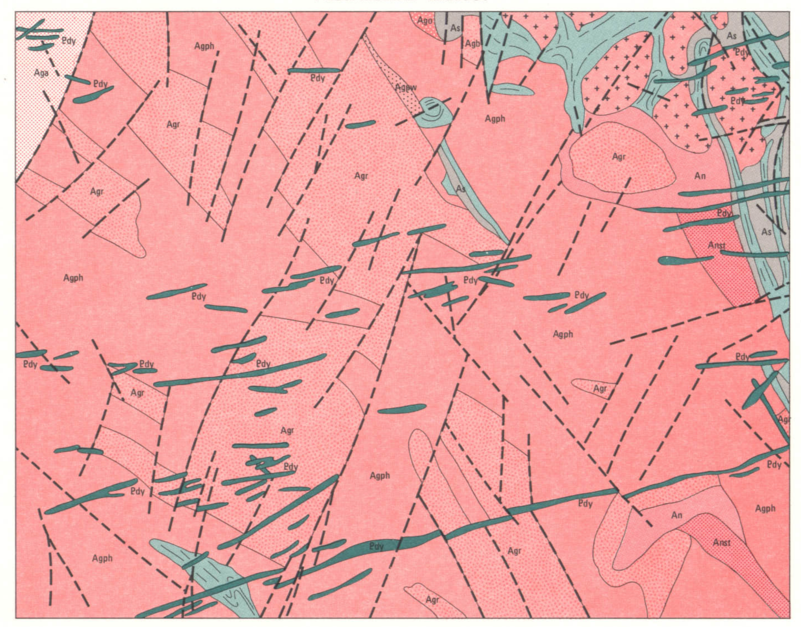
5000 Metres — 0 — 5 — 10 — 15 — 20 — 25 — 30 Kilometres

TRANSVERSE MERCATOR PROJECTION

ZONE 51 AUSTRALIAN MAP GRID

### PRECAMBRIAN GEOLOGY

Intra-greenstone granitoid
Metamorphosed felsic, mafic and ultramafic rock

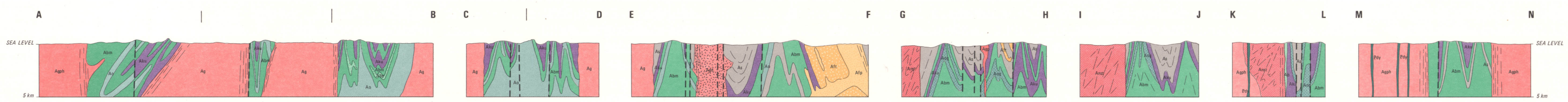


Scale 1: 1 000 000

### DIAGRAMMATIC SECTIONS

NATURAL SCALE

SECTION A-B — SECTION C-D — SECTION E-F — SECTION G-H — SECTION I-J — SECTION K-L — SECTION M-N



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