GEOLOGICAL SURVEY OF WESTERN AUSTRALIA

REPORT 35

GEOLOGY OF THE GRANITE–GREENSTONE TERRANE OF THE KALGOORLIE AND YILMIA 1:100 000 SHEETS, WESTERN AUSTRALIA

by
W. M. HUNTER

DEPARTMENT OF MINERALS AND ENERGY

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Geological Survey of Western Australia
100 Plain Street
EAST PERTH Western Australia 6004
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Geology of the granite–greenstone terrane of the Kalgoorlie and Yilmia 1:100 000 sheets, Western Australia

by W. M. Hunter

Abstract

The Kalgoorlie and Yilmia 1:100 000 sheets cover an economically important granite–greenstone terrane around Kalgoorlie and Coolgardie, 600 km east-northeast of Perth. Three categories of Archaean rocks are described — supracrustal, hypabyssal, and granitoid. A complex group of Cainozoic eluvial, alluvial, and playa deposits form extensive cover in this area.

The supracrustal rocks consist of lava flows, pyroclastic and hydroclastic rocks, and sedimentary rocks. The lava flows comprise komatiite, high-Mg basalt, and porphyritic tholeiite. Volcaniclastic rocks range in composition from felsic to intermediate and include tuff breccias, tuffs, and epiclastic sedimentary rocks. A terrigenous clastic unit of conglomerate and sandstone concludes the sequence.

The hypabyssal rocks include layered gabbro, dolerite, and felsic to intermediate porphyries. Gabbro and dolerite occur mainly within the sequence of lava flows but can occur locally within the volcaniclastic pile. Large bodies of felsic to intermediate porphyry are restricted to the volcaniclastic pile, but there are abundant small porphyry units throughout the igneous sequence.

Granitoid rocks occur both within and between major greenstone belts but their age relative to greenstone deposition is unknown. They are mainly monzogranite in composition but granodiorite and tonalite bodies occur locally.

The supracrustal and hypabyssal rocks are generally steeply inclined and occupy linear to arcuate belts with a broad north-northwesterly trend. The rocks have undergone pervasive, but heterogeneous, polyphase folding accompanied by shearing; upper greenschist to lower amphibolite facies assemblages predominate.

The succession comprises two stratigraphic groups and an overlying formation. The lower Coolgardie Group contains basalt flows (Burbanks Formation) which are intruded by layered gabbro (Three Mile Sill) and overlain by komatiite flows (Hampton Formation). The upper Black Flag Group contains felsic volcaniclastic rocks (Spargoville Formation) which are intruded by gabbro–dolerite (Powder Sill) and locally overlain by intermediate volcaniclastic rocks (White Flag Formation). The upper group is disconformably overlain by terrigenous clastic rocks (Kurrawang Formation).

Dolerite dykes, which intruded the deformed Archaean rocks at about 2.4 Ga, are divided into two groups based on dyke orientation and magnetic polarity.

Economic production on the Kalgoorlie and Yilmia sheet areas has been sporadic despite the diversity of resources. Several large historical gold deposits have recently being revived as medium to large, low-grade opencut operations. The nickel potential of the ultramafic rocks of the region has been thoroughly investigated; only two mines were established, but both are now closed.

Keywords: granite–greenstone terrane, Archaean, structural geology, metamorphism, stratigraphy, Kalgoorlie, Yilmia, Eastern Goldfields Province, Yilgarn Craton.

Introduction

The KALGOORLIE and YILMIA* 1:100 000 sheets (3136 and 3135) cover an area of 2640 km^2, 450 km east of Perth, bounded by latitudes 30°30' and 31°30' south and longitudes 121°00' and 121°30' east (Fig. 1). They lie within the Eastern Goldfields Province of the Yilgarn Craton and include parts of the Coolgardie and East Coolgardie Mineral Fields.

Current land use is confined to KALGOORLIE and northern YILMIA where mineral exploration and mining coexist with pastoral leases. There are many stations rough-grazing sheep and there have been sporadic attempts to grow cereals northwest of Coolgardie. Horse Rocks Station and land west of the Coolgardie–Esperance Highway (part of Mandilla Station) have reverted to Crown Land, while the remainder of YILMIA is vacant Crown Land which was extensively exploited for timber in the first half of this century. The Kurrawang Aboriginal Reserve is located 15 km southwest of Kalgoorlie. Flora and fauna reserves are located at Burra Rock and 12 km southwest of Kalgoorlie, and there are forest reserves in the Kangaroo Hills, Saddle Hills, and Horse Rocks areas.

Access throughout KALGOORLIE and northern YILMIA is generally good, except in the southwest of YILMIA where access is by sparse, poorly defined tracks blazed by early explorers and timber cutters. The Great

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

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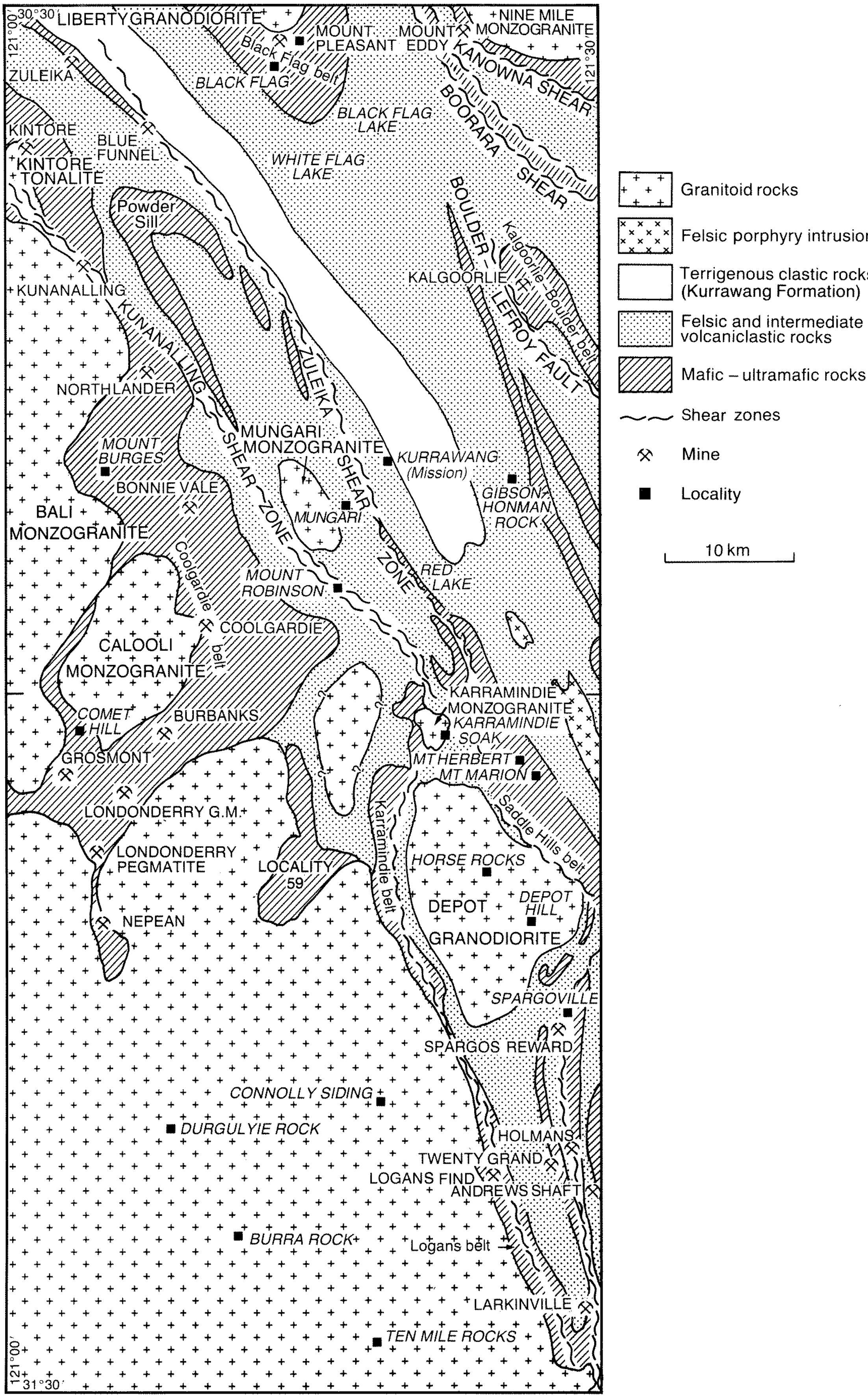


Figure 1. Localities and names on the KALGOORLIE and YILMIA 1:100 000 map sheets.

Eastern and Kalgoorlie–Meekatharra Highways traverse southern and eastern KALGOORLIE respectively, and the Coolgardie–Esperance Highway traverses the northeast corner of YILMIA. Unsealed, but well formed, roads pass through the western part of the sheets, linking Coolgardie with Carbine to the northwest and Hyden to the southwest. The Muja–Kalgoorlie 220 kV power line, the Mundaring–Kalgoorlie water pipeline, and the abandoned Perth–Kalgoorlie narrow-gauge railway run parallel to the Great Eastern Highway. A network of abandoned 'woodlines' cover both sheet areas. The remnant formations to these narrow-gauge railways have produced distinct airphoto lineaments which are useful aids to navigation. Some have been kept clear and are currently used for vehicle access.

The administrative centres for this region are Coolgardie (pop. 891*) and Kalgoorlie (pop. 19 848*). A small minesite settlement exists at Nepean, while individual dwellings are to found at Hampton Plains, Spargoville, and extant pastoral stations.

Early geological discussions of the KALGOORLIE–YILMIA sheet areas are listed in a bibliography of the early geological studies and exploration of Western Australia compiled by Maitland (1899). Various geological investigations by the Geological Survey of W.A. (GSWA) in the vicinity of KALGOORLIE have been published in a number of annual reports and bulletins, a list of which is given in GSWA Bulletin 107 (McMath et al., 1953, p. 33–35). The more important GSWA bulletins for this area are: Blatchford (1899, 1913), Gibson (1908), Honman (1914), Feldtmann (1916, 1925), Stillwell (1929), Jutson (1950), and McMath et al. (1953). More recently a review was made by Williams (1974c) 'of the geological investigations of the Eastern Goldfields Province', and included a bibliography to December 1972.

The first regional geology surveys at 1:250 000 scale in the KALGOORLIE–YILMIA region were completed by Sofoulis and Bock in 1963 and Kriewaldt in 1968. A revision of the BOORABBIN 1:250 000 sheet was completed in 1984 (Hunter, 1989). Keats (1987) has completed a detailed study of the geology of the Kalgoorlie–Boulder township and environs, and Swager (1989) has described the structural geology of that region. The Bureau of Mineral Resources (now the Australian Geological Survey Organization) published the results of an aeromagnetic survey over the KALGOORLIE and BOORABBIN 1:250 000 sheets in 1960 and 1963 respectively.

Since 1965 the region has experienced a period of intense exploration for nickel and other base metals and, more recently, for gold. The results of these explorations are given in statutory reports and are available for viewing as microfiche from the open file system of the Geological Survey of W.A. library. Gemuts and Theron (1975) produced a synthesis of the geological advances during the nickel boom exploration. Their regional map and sequential stratigraphy provided the first refinement to the cyclical stratigraphic model of Williams (1969, 1970, 1974a). More recent work (e.g. Griffin et al., 1983; Hunter, 1988a,b) is tending to favour a model of complex structural repetition of simple (possibly single) sequences rather than the earlier polycyclic models.

This report discusses the geological mapping of the KALGOORLIE and YILMIA 1:100 000 sheet areas carried out by the author from 1981 to 1985 (Hunter, 1988a,b).

Physiography

KALGOORLIE and YILMIA are situated in the southern-central portion of the Salt Lake or Salinaland division of Jutson (1950) and lie within the Kalgoorlie Natural Region of Clarke (1926). On the basis of vegetation, soil association and physiography, Beard (1972, 1976) divided these sheets into four vegetation systems.

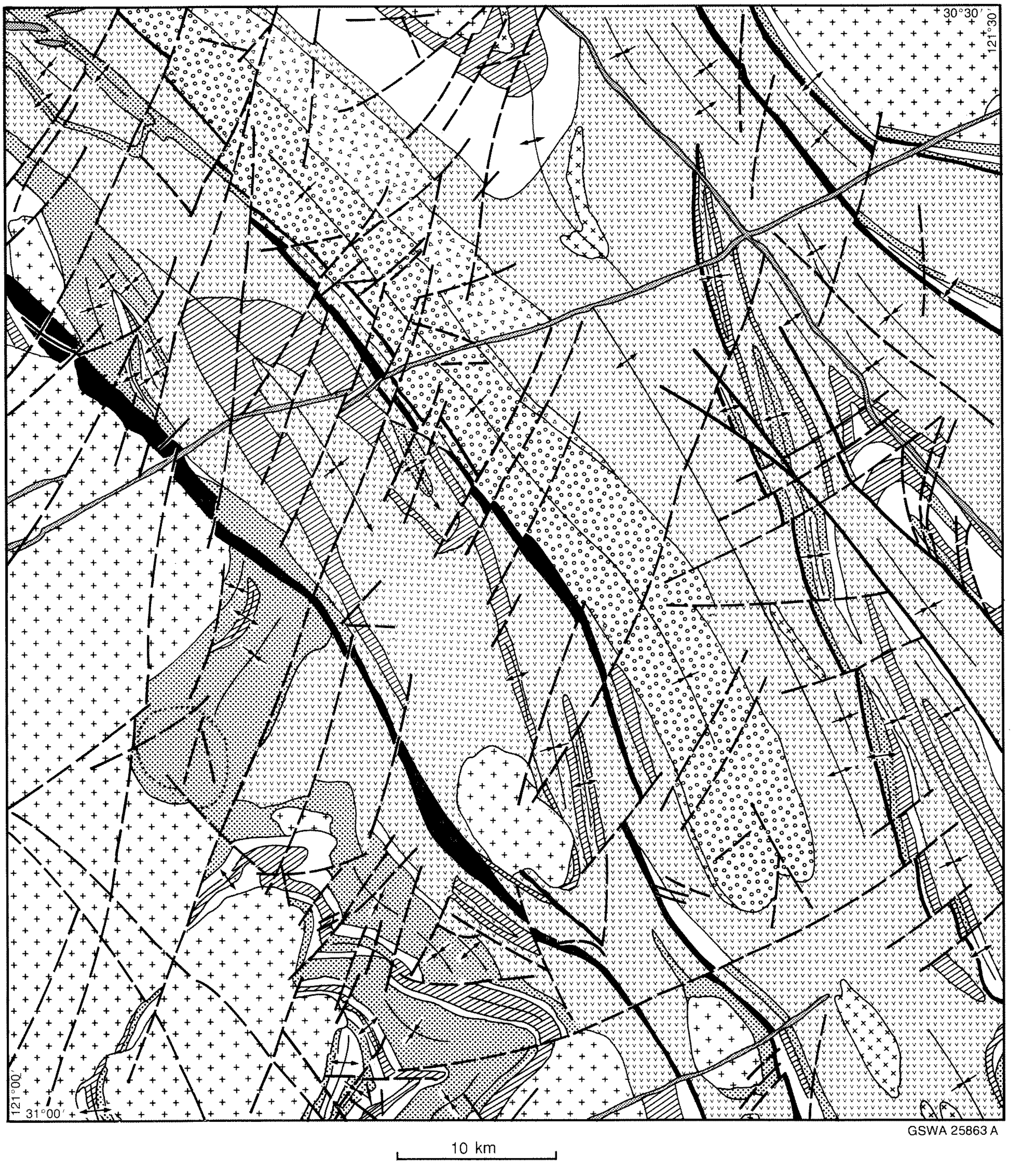
The southwestern corner of KALGOORLIE and the central western part of YILMIA is part of the Boorabbin System and consists of weakly dissected upland development on granitoid rock. This upland area is the Old Plateau of Jutson (1950) and comprises undulating sandplain up to 500 m in altitude and valleys down to 380 m ASL. Small, low-lying granitoid outcrops are scattered throughout the area but are most common under laterite scarps to the west of major trunk drainages (the New Plateau).

The southern quarter of YILMIA is part of the Cave Hill System and also consists of granitic upland with peaks of similar altitude. However, strong dissection has removed much of the sandplain cover of the Old Plateau, incising narrow, deep drainage channels and exposing low granitic hills as interfluves. The topographic relief in this area may be greater than 50 m with a range in altitude from 300 m in the trunk drainage up to 480 m in the interfluves.

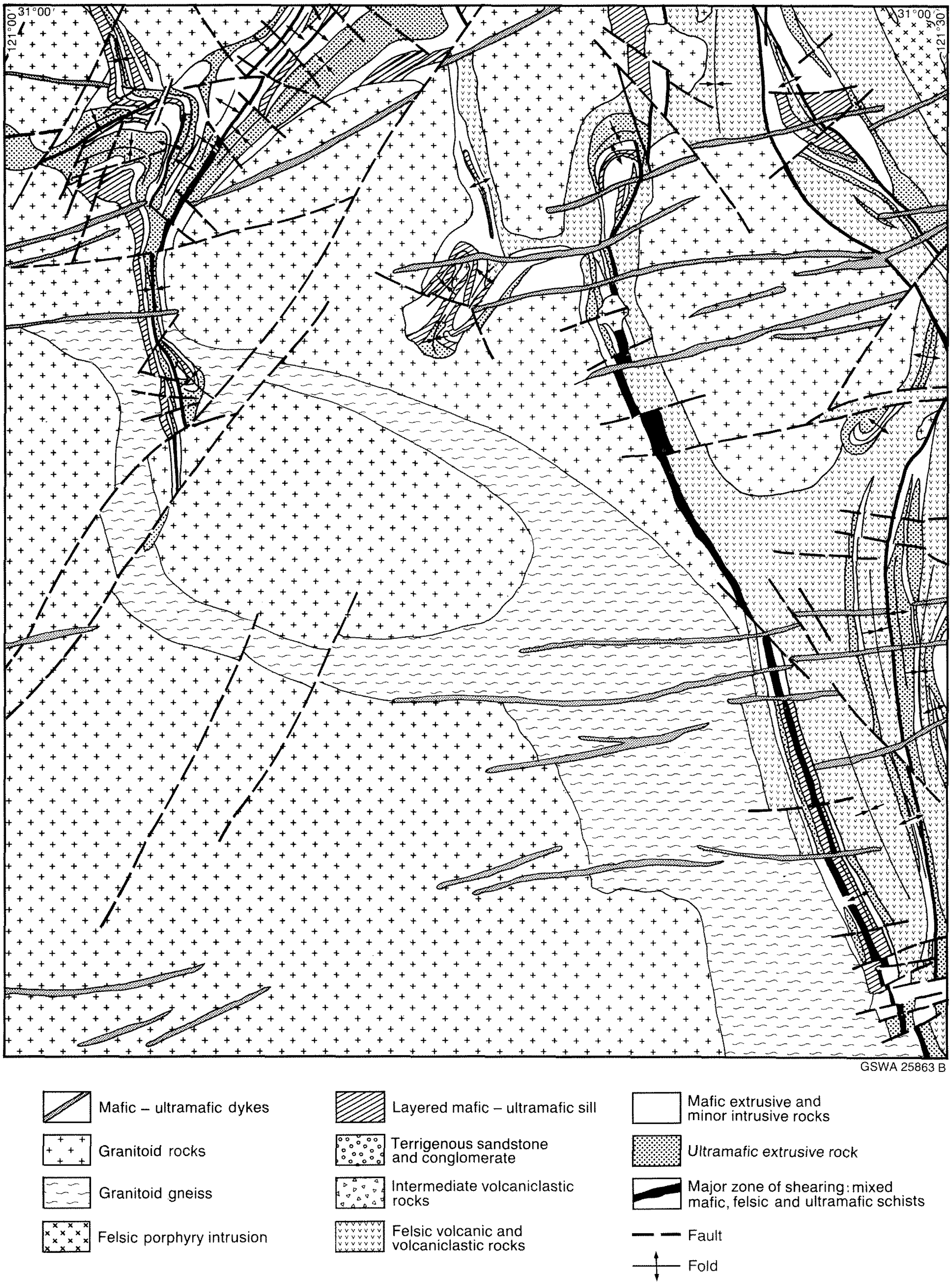
The northeast half of YILMIA and southeast half of KALGOORLIE forms part of the Coolgardie System, and consist of north-northwest trending ranges of hills, with rocky summits and broad talus flanks composed of mafic and ultramafic volcanic and felsic volcaniclastic rocks. The relief is about 100 m, and internal and external drainage is complex and mainly fault controlled. The northeastern half of KALGOORLIE (Kunanalling System) is underlain by both granitoids and greenstones, which form tracts of undulating country with low relief. Thick mantles of eluvium and soil cover hills and broad colluvial plains in this area.

A study of the early Cainozoic drainages (van der Graaf 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 and KALGOORLIE 1:250 000 sheets, thus modifying the view of Beard (1976) that the trend

* Population statistics from the 1981 census.



Figures 2A, 2B. Solid geology interpretation of KALGOORLIE and YILMIA 1:100 000 map sheets.


31°00'
121°00'
31°00'
121°30'
GSWA 25863 B
Mafic – ultramafic dykes
Granitoid rocks
Granitoid gneiss
Felsic porphyry intrusion
Layered mafic – ultramafic sill
Terrigenous sandstone and conglomerate
Intermediate volcaniclastic rocks
Felsic volcanic and volcaniclastic rocks
Mafic extrusive and minor intrusive rocks
Ultramafic extrusive rock
Major zone of shearing: mixed mafic, felsic and ultramafic schists
Fault
Fold

of the divide is southwest–northeast. The divide, which has an elevation of 480–500 m within BOORABBIN, separates the northerly and the westerly flow of the Boorabbin palaeoriver system from the easterly flow of the Yindarlgooda and Lefroy palaeorivers. The presence of the major trunk drainages and the abundant minor divides and interfluves indicates an ancient period of high precipitation. Waning of this pluvial regime and the onset of an arid to semi-arid climate caused the choking of drainage by sediments (eolian and fluvial) and the development of the current playa-lake systems. Dating the drainage systems is imprecise but van der Graaf et al. (1977) have argued that significant flow ceased prior to the Middle Miocene and probably by Late Eocene. The maximum age is certainly post-Early Cretaceous to the east but there is some evidence within the Precambrian shield area for a Permian age for some systems. The characteristic tear-drop shape to the playa lakes is controlled, in part, by basal geology and, in part, by the dominance of westerly winds during the winter wet season. Erosion is currently active on the western margins of these lakes, while eolian deposition occurs on the eastern margins.

Climate and vegetation

The climate of the region is semi-arid with hot summers and cool to mild winters. Average diurnal temperature ranges measured at Kalgoorlie are greatest in January to February (34–18°C) and least in July (16–5°C). Rainfall averages 250 mm per annum with the wettest period being May to August. Evaporation greatly exceeds precipitation for most of the year, and in the northeastern part of the BOORABBIN 1:250 000 sheet, evaporation averages 2200 mm per annum.

There is a close correlation between photo-interpreted geology and the six plant formations delineated by Beard (1972, 1976); this indicates that 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, shallow lateritic soils, and degraded granitic outcrops (*Czs, Czl,* and *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 outcrops of granitoid rock (*Ag*) with aquatic plants in pools, and shrubs in crevices and the occasional soil patches. On leached, granitic eluvial and alluvial soils (*Czg* and *Czc*), 'Mallee and Sclerophyll Woodland' form open to closed eucalypt shrub or woodland with a 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*).

The Western Australian Museum is conducting a flora and fauna survey of the Eastern Goldfields of Western Australia, publishing the results in its Records series. The survey in the KALGOORLIE area has recently been published (McKenzie and Hall, 1992), while the publication on the YILMIA area is in preparation.

Regional geology

KALGOORLIE and YILMIA lie in the eastern part of the Yilgarn Craton, on the western margin of the north-northwest trending Norseman–Wiluna belt. Interpretations of the crustal development of the Yilgarn Craton have been discussed by Gee et al. (1981), Groves and Lesher (1982), and Griffin (1990b).

The greenstones have undergone several stages of pervasive deformation and metamorphism, punctuated by granitoid intrusion. Regional metamorphism reached upper greenschist to lower amphibolite facies but primary textures are widely preserved and enable many protoliths to be identified.

In this report the regional aspects of the geology are discussed, with amplification from observations of selected areas. The description of Archaean lithologies is divided into four groups — supracrustal rocks, mafic intrusions, felsic intrusions, and granitoid rocks (see Fig. 2). Interpretations of the stratigraphic succession and structure are presented, and the regional geology is discussed within sub-areas of the sheets. The principal occurrences of gold, nickel, and industrial minerals are reviewed and their production statistics presented. The reader is referred to Keats (1987) and Swager (1989) for more detailed discussions of the geology, structure, and mineralization of the Kalgoorlie–Boulder mining locality.

Until the middle of the twentieth century, geological investigations in the region concentrated on extant mining localities. Larger mines were described in detail (e.g. Blatchford, 1913; Gibson, 1908; Feldtmann, 1916, 1925; Stillwell, 1929) and attempts were made to elucidate local stratigraphy and structure (e.g. Blatchford, 1899; Forman, 1937a; Honman, 1914; McMath et al., 1953). More recently there has been emphasis on regional mapping and synthesis (e.g. Sofoulis, 1963; Kriewaldt, 1969; Glikson, 1971a,b; Gemuts and Theron, 1975; Martyn, 1987).

The first major synthesis of the stratigraphy in the Kalgoorlie region was presented by Forman (1937a) and is summarized in Table 4. He proposed that the greenstones of the Kalgoorlie Mining Centre formed the base to a thick felsic volcanic and sedimentary succession which was intruded at various intervals by 'granites' and dolerites.

McMath et al. (1953) integrated reconnaissance mapping with detailed mine examinations in the Coolgardie area. Their maps defined the trends of a major mafic–ultramafic sequence, and led to the first interpretation of the structure and stratigraphy. They proposed a thick, complex succession (Fig. 26) comprising four horizons of ultramafic rock alternating with four basalt horizons; the upper two basalts were separated by a major gabbro sill. They suggested that the current disposition of lithologies arose through regional doming followed by a suite of parallel cross-folds and by granitoid intrusion.

In the first edition of the BOORABBIN 1:250 000 Explanatory Notes, Sofoulis (1963) maintained the overall configuration of lithologies from the previous investigations but delineated further divisions of both mafic and ultramafic units. In mapping the KALGOORLIE 1:250 000 sheet, Kriewaldt (1969) showed there was broad northerly continuity of the Kalgoorlie and Coolgardie greenstone belts.

The greenstone succession at Kalgoorlie was subdivided by Woodall (1965) (see Table 4). He recognized a lower ultramafic body which was overlain by two basalt units separated by dolerite and slate. Felsic to intermediate volcanic and clastic rocks formed the upper part of the succession which was separated from the basalt by a layered dolerite sill.

The similarity of rock sequences across the KURNALPI 1:250 000 sheet area led Williams (1969, 1970) to the conclusion that cyclical volcanism had occurred in this region (see summary in Table 3). He proposed that at least three volcanic cycles, changing from ultramafic through mafic lavas to felsic volcanic and sedimentary rocks, occurred northeast of Kalgoorlie. Gemuts and Theron (1975) arrived at a similar conclusion when they integrated exploration data from the Norseman–Coolgardie region. They proposed eight sequences which represented associations of mafic and ultramafic rocks, felsic volcanic rocks, and conglomerates and greywackes. These sequences were grouped by Gemuts and Theron into three volcanic cycles, but their distinction between sequences of similar rocks is rather tenuous.

This report recognizes the same gross lithological units as those discussed above; however, the recurrence of similar sequences is attributed here to structural, not stratigraphic, repetition. The lithological differences between sequences of similar rocks is due mainly to local facies variations. The succession is best determined in the Coolgardie–Kurrawang–Black Flag region, but can be traced, with increasing structural complexity, through Spargoville to the south. Basalt forms the lowermost unit. It is intruded by several gabbro–dolerite sills and punctuated by interflow sedimentary rocks, and succeeded by komatiite flows that contain a thin basalt horizon. A thick, heterogeneous pile of felsic volcanic and volcaniclastic rocks overlies the ultramafic unit, and intermediate volcaniclastic rocks occur locally at the top of the pile. The top of the proposed succession is marked by terrigenous clastic rocks, in part derived from the underlying volcaniclastic rocks.

Nomenclature

The usage of some lithological terms is commonly debated and controversial terms used in this report are defined here. Komatiites are extrusive rocks with high-Mg and low-Al chemistry, which commonly display distinctive mineral textures (Arndt and Brooks, 1980; 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 process of fragmentation, dispersion, and deposition (Fisher and Schmincke, 1984). For the granitoid rocks the nomenclature system of Streckeisen (1976) is used.

Archaean supracrustal rocks

Metamorphism of the supracrustal sequence has produced a suite of lithologies indicating general attainment of upper greenschist to lower amphibolite facies conditions. However, diagnostic textures at the mesoscopic and microscopic levels are commonly preserved and the protoliths readily identified. Throughout this section, therefore, the prefix 'meta-' has been omitted from the lithological name and units are discussed in terms of their original nature.

Basalt (*Ab*)

Where complex interleaving and strong deformation have produced composite schists comprised of unassigned basalts with minor intrusive rocks, the general symbol (*Ab*) has been given to the lithological unit (Fig. 3).

High-Mg basalt (*Abm*)

A thick sequence of high-Mg basalts (*Abm*) containing minor, thin interflow sedimentary rocks occurs throughout KALGOORLIE and YILMIA. The thickness of the pile in the Coolgardie area is at least 500 m, whereas in the Saddle Hills it approaches 1500 m. In the latter case, however, there is considerable brecciation and drag folding within interflow sedimentary rocks, suggesting some tectonic thickening has occurred. A large amount of crustal shortening and slicing precludes any thickness estimate for the other belts.

The high-Mg basalt sequence is overlain by a thick succession of ultramafic flows and the boundary is marked by a thin, grey shale horizon. The base of the basalt is not exposed and the substratum is unknown.

The mesoscopic features of these lavas are varied in their development and degree of preservation but their association characterizes a typical suite of dominantly high-Mg basalts which were extruded in, or near, a shallow-water environment.

Rock type

The basalt is typically fine to medium grained, and has a dark green to black, fresh surface which changes to a pale green to mid-green, weathered veneer. Where higher metamorphic grade has prevailed, grain size coarsening may occur and the rock is darker.

The extent and thickness of individual basalt flows is unknown as generally limited exposure prevents lateral or vertical correlation. However, in the Coolgardie and Saddle Hills areas, pillowed horizons which recur every 10 to 20 m can be traced along strike for several hundred metres, indicating that flows are thin and laterally extensive.

Figure 3. **Deformed and metamorphosed mafic rocks (*Ab*), west of Horse Rocks.**

Pillow structures are common in the upper portions (1–5 m) of flows (Fig. 4) and, despite pervasive deformation, they provide good evidence of younging direction (Borradaile, 1982). Radii of pillows are commonly in the range of 10–50 cm, although rare examples up to 1 m have been recorded. Large pillows may have multiple cusps (usually two). The form of the pillows is commonly defined by millimetre-scale banding of metamorphic chlorite, feldspar, and amphibole which replace rinds of chilled magma and/or vitric fragments. Further, there is textural and commonly mineralogical contrast between pillow and interstices; good examples pillows can be seen in 'The Gorge' 6 km southeast of Coolgardie.

A common feature of these basalts, and one which characterizes them as high-Mg in affinity (Arndt and Nisbet, 1982), is the presence of ocelli (Fig. 5). These pale, spherical bodies occur scattered within massive horizons of basalt or in concentric zones within pillows. They vary in size from a few millimetres to 1 cm between occurrences, and a radial decrease in size within pillows is also apparent. Concentric zoning may be present within individual ocelli.

Flow-top breccias are not common in the basaltic sequence but, where present, they form thin (< 0.5 m) horizons providing evidence of bedding orientation. Fragmentation of blocks is generally small scale, i.e. 10–20 cm, and may be accompanied by infill of fine fragments of chilled lava or vitric shards. These features indicate the fragmentation may be, at least in part, hydroclastic in origin. Southwest of Bakers Find, these breccia horizons have been conduits for late stage hydrothermal fluids which have coated fragments with azurite and malachite.

Figure 4. Pillowed high-Mg basalt (*Abm*) in The Gorge, southeast Coolgardie.

Figure 5. Ocellar structures in high-Mg basalt (*Abm*), southeast of Kalgoorlie. These are spherical concentrations of leucocratic minerals in concentric or radial patterns.

The metamorphic grade of high-Mg basalt is in the range of low to middle amphibolite facies and may reach upper amphibolite facies. The style of metamorphism evident in these rocks varies between static and dynamic, both along and across the greenstone belts, 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 relative extent of tectonic uplift.

The high-Mg basalt mineralogy is typical of the metamorphic grade, comprising assemblages of amphibole and plagioclase with variable proportions of epidote, chlorite, quartz, carbonate, and accessory magnetite, ilmenite, sphene, and apatite. Amphibole constitutes 75–90% of the rock, although in the more differentiated varieties there is as little as 60%. Actinolite is the most common amphibole type but more hornblendic examples occur locally. In the southern Karramindie belt and in the area north of Spargoville, hornblendic amphibole is predominant and there is a high degree of textural equilibrium in both static and dynamic metamorphic styles. This indicates that sustained elevated temperatures, probably related to intrusion of the Depot Granodiorite, accompanied development of the marginal shear zones.

Plagioclase constitutes 10–25% of the rock and occasionally reaches 40%; composition ranges from oligoclase to labradorite and relates to the grade and extent of metamorphism, which varies from area to area. Plagioclase and quartz form a granular leucocratic groundmass to the amphiboles, either as irregular interstitial tracts or as pseudomorphs of bladed primary crystals. The plagioclase grains are generally equant, with interlobate to polygonal textures which may form straight-margined mosaics with 120° triple points. In the plagioclase, twinning is patchily developed from one area to another, and zoning is uncommon.

Ocellar structures present in the high-Mg basalt tend to have the same mineralogy as the host but with higher proportions (50–60%) of plagioclase. Concentric patterns visible in hand specimen are due to changes in plagioclase content as well as variations in grain size. The textures commonly mimic those of the host with plagioclase complexly intergrown with acicular or skeletal amphiboles. Ocelli boundaries are generally sharp, and, despite recrystallization, the transition occurs over the space of a few grains. Quartz and carbonate may also be present. Ferguson and Currie (1972) favoured a mechanism involving silicate liquid immiscibility rather than an amygdaloidal origin for the formation of similar bodies in basalts of the Barberton Mountain Land, Transvaal. Amygdaloidal or vesicular structures are rare in basalts on KALGOORLIE and YILMIA.

Original igneous textures in the basalts are preserved in areas of low strain but become progressively obscured with increasing strain and degree of discordant metamorphic recrystallization. Metamorphic amphibole forms single crystals, multiple blades, or trains of granular crystals pseudomorphing original plumose pyroxenes. With progressively higher strain, the fronds of these structures are rotated into parallelism, defining schistosity, but acute intersections at branching points are usually discernible. Dusty opaques excluded from pyroxenes during recrystallization commonly preserve the protocryst form, despite discordant amphibole growth and deformation. In those rocks with more basaltic to doleritic textures, broadly bladed or subophitic platy pyroxenes are pseudomorphed by multi-grain plates or granular masses of amphibole.

South of Spargoville, apparent grain-size coarsening in the chilled lava portions of basalt pillows has been commonly noted. Amphibole grows as fine, short needles in bow-tie sheaves or rosettes; the aggregates having diameters up to 5 mm. In the field they have the appearance of pseudomorphs after equant platy pyroxenes, and the rock has the appearance of metagabbro. However, the common occurrence of ocelli delineating pillow forms reveals the true nature of the protolith.

Discussion

The ubiquitous high-Mg basalts are identified by their 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 also abundant.

Metamorphic grain-size coarsening is prevalent in basalts on the Spargoville–Larkinville region where microgabbro to gabbro pseudo-textures may have been produced by overgrowths of metamorphic amphibole. North of Andrews Shaft there are some excellent examples in which rosetted amphiboles, 2–3 mm across, form in interstices between feldspathic ocelli.

The presence of tholeiitic basalts in this area has long been mooted (Hallberg, 1972; Gemuts and Theron, 1975) but nowhere have they been unequivocally demonstrated. If they do occur, then they are subordinate to the more easily identified high-Mg basalts.

Horizons of 'dolerite' have, in the past, been mapped within basalt as swarms of sills (where they are medium to coarse grained) or as interbedded tholeiitic basalts (where they are fine grained). However, in the Saddle Hills it is clear that such horizons are variations within individual flows of high-Mg basalt. They form at the centre or towards the base of flows and commonly constitute changes from: variolitic to basaltic or doleritic texture; fine to medium or coarse grain size; and low to moderate feldspar content. These horizons are interpreted as zones of slower cooling rate and of differentiation within flows. The extent to which the variations develop appears to be directly proportional to the thickness of the flow.

At the southern end of the Karramindie belt, pale green to pink pods and strips of calc-silicates at the tops of flows give an unusual streakiness to colour and texture. They may represent metamorphic products of primary spilitic alteration or they may be hydrothermal products associated with a later shear zone marginal to the Depot Granodiorite.

Deformation has affected the basalts to a lesser extent than the gabbro but in a similar style of spaced occurrences of high strain (see section on 'Mafic intrusive rocks'). Where thick zones of apparent low strain occur, such as the north Coolgardie, Burbanks and Saddle Hills areas, deformation has been taken up along interflow sedimentary (grey shale) horizons. This may be evident as complex drag folding or brecciation within the metasedimentary rock. Elsewhere, more general deformation produced a layer-parallel foliation throughout the basalt sequence which may be intense (Spargoville–Larkinville) or moderate (Grosmont and near Karramindie Soak). In the southern half of the Karramindie belt, intense deformation related to a late shear zone has produced compositionally banded amphibolites possibly derived from quartz-veined, pillowed basalts. Primary structures, such as ocelli and pillows, provide good indication of strain, as they are flattened and commonly elongated as a subvertical lineation.

In the upper portions of the basalt sequence there are two thin horizons with distinctive lithologies, asymmetric disposition, and persistent occurrence which constitute good stratigraphic markers. The lower horizon is a feldspar-phyric basalt (*Abp*), which is described fully in a later section. This horizon is up to 150 m thick in places but is generally narrower and locally tectonically thinned. It is characterized by clusters of feldspar phenocrysts which are set in a fine- to medium-grained matrix. Boundaries between the feldspar-phyric basalt and the high-Mg basalt are sharp. Between this unit and the overlying ultramafic lavas is a very thin, poorly outcropping horizon of mixed sedimentary rocks (*Af*) comprising interbedded grey shale (*Ash*) and felsic porphyry schist (*Afs*) derived from volcaniclastic rock. This upper horizon is auriferous and its surface trend is indicated by lines of old gold workings. One major grouping of mines, at Burbanks, is located on this trend.

Basaltic agglomerate (*Aba*)

A mafic unit, up to 500 m thick but of limited lateral extent, ranging from agglomerate to lapilli tuff (*Aba*) occurs on the Red Lake peninsula, 7 km southeast of Mungari. The unit is overlies high-Mg basalt and is overlain by grey shales and felsic volcaniclastic rock, and forms part of a tight anticline which is sheared to the west. Northwest of Karramindie (around AMG 427690*), the unit is bounded by a mylonitic shear zone to the east, and high-Mg basalts and a thick gabbro sill to the west.

Horizons of crystal and lithic tuff are scattered throughout the area; however, they are commonly difficult to recognize in deformed high-Mg basalts due to their similarity to flow-top breccias.

* Localities are specified by the Australian Map Grid (AMG) standard six-figure reference system. The first group of three numbers (eastings) and the second group (northings) together define the locality position, on the map sheets discussed, to within 100 metres.

Rock type

The agglomerate contains subangular to rounded, elongate clasts of basalt, dolerite, felsic volcaniclastic rock, and sparse, fine- to medium-grained, amphibole-rich tonalitic granitoid. There is a gradational increase in the proportion of felsic clasts up through the unit. Clast-size distribution is polymodal and individual clasts are rarely larger than a few centimetres. There is a slight increase in clast size towards the base of the unit where some blocks are more than 10 cm long. Clasts are aligned subparallel to an upright anastomosing foliation which is more strongly developed in the matrix than the clasts.

Thin sections of the basalt fragments reveal internal flow structures, amygdales, and fine plagioclase phenocrysts. Foliation is common only at the margin of clasts where they abut a moderately foliated matrix. In the agglomerate, middle amphibolite facies metamorphism has produced an assemblage of hornblende (olive green to light bluish-green), quartz, andesine and minor opaques and apatite; retrograde metamorphism, probably related to intrusion of the Karramindie Monzogranite, has introduced rare yellowish pumpellyite. The general texture of the matrix is granoblastic and polygonal to interlobate for plagioclase, while amphibole forms felted masses.

On the Red Lake peninsula, the agglomerate matrix is composed of vitric shards and variably comminuted fragments of the constituent felsic and mafic clasts. However, northwest of Karramindie Soak, the matrix is a foliated, fine- to medium-grained, hornblende-bearing tonalite. The similarity in textures and metamorphic grade indicate that the granitoid matrix was metamorphosed with the basaltic clasts it supports.

Discussion

These agglomeratic deposits are unusual in having a matrix which consists of a mixture of rock types. Other fragmental mafic rocks associated with felsic hosts occur at this stratigraphic level in KALGOORLIE and are described in under 'Mafic intrusive rocks'.

Glikson (1972) gave a detailed petrographic description of the rocks on the Red Lake peninsula and interpreted them as mafic flow-breccias. This style of eruption is not consistent with the low-viscosity mafic and ultramafic lavas which dominate this region and does not adequately explain the style of mixing of juxtaposed lithologies.

Northwest of Karramindie Soak (around AMG 425690), the intimate association of felsic and mafic igneous rocks is interpreted as indicating contemporaneity and that some magma confluence caused Plinian-style eruptions with the ejection of dominantly mechanically mixed pyroclasts. Textures at the macroscopic and microscopic levels in these rocks show primitive development of amygdales and plagioclase phenocrysts; none of the characteristic textures of high-Mg basalts are seen. The basalt is probably comagmatic with the feldspar-phyric basalt (*Abp*).

On the Red Lake peninsula, both tholeiitic basalt and high-Mg basalt–dolerite fragments are mixed with felsic volcaniclastic rocks. This association is interpreted as a hydroclastic deposit in which fragmentation occurred as a wedge of mafic magma entered the base of the unlithified, probably wet, felsic volcaniclastic deposits. Turbulent disruption occurred through volatile streaming when water was superheated by the incoming magma.

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 called 'cat-rock' (alluding to the mottled coat of a native marsupial). The unit is well exposed in the Black Flag, Burbanks, and Hampton Locality 59 areas but becomes progressively obscured by deformation and recrystallization southward. Porphyritic basalt has not been recognized north of Coolgardie or in southeast YILMIA.

This basaltic horizon has a thickness of 150–200 m in areas of low strain, diminishing to a few tens of metres in zones of high strain; its maximum thickness is seen at Black Flag and west of Burbanks. Contacts with the high-Mg basalts are invariably sharp but there are no apparent chilled margins. No internal boundaries have been found within the porphyritic basalt and so it appears to be a single horizon. There is some textural variation within the unit, particularly on the regional scale (Figs 6A-C).

Rock type

The grain size of the matrix ranges from fine to coarse but rarely shows a broad range at one locality. At Hampton Locality 59, grain-size grading within the unit appears to reflect preferential metamorphic coarsening (Fig. 6A). The size and abundance of feldspar megacrysts may also vary at outcrop scale. They are commonly 1–1.5 cm in length but can be greater than 2 cm, and are euhedral to subhedral. Feldspar megacrysts typically occur as clusters of many (commonly 4–6) feldspar crystals; it is only where feldspar is scarce that they occur as individual crystals. The relative abundance of megacryst clusters to individual crystals is highly variable and apparently unsystematic, although clusters tend to concentrate higher in the unit near Black Flag (Fig. 6B).

The composition of the porphyritic basalt is closer to tholeiitic than to high-Mg basalt and has, therefore, greater affinity with the gabbro sills (*Aog*) of this area. Relict igneous textures are commonly preserved, except in zones of high strain, and indications of both basaltic flow and small intrusion are found. Metamorphism at low to middle amphibolite facies has replaced the primary mineralogy of the basalt, while later metamorphism, associated with shearing, has modified the first metamorphic assemblage.

In the porphyritic basalt, amphibole is hornblendic and occurs as acicular to prismatic crystals which are locally sieved. In the more deformed localities, the

Figure 6A. Porphyritic basalt (*Abp*), Hampton Locality 59, containing abundant finer-grained feldspar megacrysts in a fine-grained matrix.

Figure 6B. **Porphyritic basalt (*Abp*), southeast of Black Flag Homestead, showing clustering of feldspar megacrysts.**

Figure 6C. **Porphyritic basalt (*Abp*), southeast of Black Flag Homestead, containing scattered feldspar megacrysts in a coarse-grained matrix.**

amphibole has a strong orientation parallel to layering. Plagioclase of andesine composition occurs as fine laths in the matrix and as euhedral megacrysts. Deformation has induced a fine granulation of plagioclase which tends to form polygonal mosaics. Plagioclase phenocrysts are well preserved in porphyritic basalt from low strain localities but elsewhere they are recrystallized to subgrains within protocryst boundaries. A characteristic feature of the metamorphosed glomero-phenocrysts is the overgrowth of amphibole; bundles of fine parallel amphibole needles nucleate at crystal boundaries and permeate the megacrysts. Total replacement occurs locally (e.g. southwest of Burbanks), producing dark mottles in the rock which, when strained, appear as streaky dark augen (Fig. 7). Minor mineral phases present in the porphyritic basalt include magnetite, quartz, biotite, leucoxene, clinozoisite, and carbonate.

Discussion

Feldspar-phyric basalts commonly occur 300–500 m below the felsic volcanic units of many Archaean greenstone belts (Green, 1975). The value of the porphyritic basalt as a marker horizon is equivocal since it is not clear whether it is wholly intrusive or extrusive. Blatchford (1913) described these 'porphyrites' at Burbanks as dykes parallel to the granite–greenstone contact, while Ward (1948) deduced they were amygdaloidal lavas with feldspar as an infilling. Miles (1946) referred to the unit in the Tindals area as 'basic extrusives' penecontemporaneous and comagmatic with the other lavas. Lack of cross-cutting relations in the 'basic porphyry' between Burbanks and Londonderry, coupled with micropetrology, led McMath (1950) and Sofoulis (1963) to similar conclusions. Further afield,

Figure 7. Metamorphosed and deformed porphyritic basalt (*Abp*), southwest of Burbanks, showing replacement of feldspar megacrysts by amphibole with the development of dark augen texture.

Farquharson (1921) compared the basic porphyry at Goongarrie to the 'dolerite' of Ora Banda; however, after finding flow banding and pillows underground at Grants Patch, Hobson (1944) concluded the unit was a flow, not a sill. Good pillow forms are clearly seen at the Gimlet South mine at Ora Banda (Witt, 1990).

South of Coolgardie, porphyritic basalt forms a thin, continuous unit at the same relative level in the stratigraphy throughout, and no evidence of transgression or bifurcation of the unit has been found.

Southeast of Black Flag Homestead, the unit shows an upward gradation from doleritic to basaltic texture which is not related to high-grade metamorphism. This is accompanied by a change in concentration of feldspar phenocrysts from scattered in the dolerite to abundant, and large, in the basalt. These variations indicate a slow cooling base to the unit and a fluid environment where the phenocrysts were buoyed towards the top.

To the southwest of Black Flag, there are a number of localities where the upper levels of the unit show good pillow structures. Where porphyritic basalt is overlain by felsic volcaniclastic rocks, there is some annealing and turbulent disturbance of the felsic rocks. This relationship suggests that the basalt was intrusive (Hunter, in prep.). Although the basaltic and felsic rocks were broadly contemporaneous, the volcaniclastic rock were deposited first and the basaltic magma intruded at the base of the wet volcaniclastic deposit. Pillows were produced by the Leidenfrost effect (Kokelaar, 1982; Mills, 1984). Local evidence suggests that the presence of pillows with clastic rocks is not diagnostic of an extrusive origin.

Komatiite (*Au, Aku, Akp*)

Ultramafic extrusive rocks occur throughout KALGOORLIE and YILMIA. The thickness of the komatiite succession is about 600 m, but outcrop thickness is dependent on local structure. Where greater thicknesses of komatiite are apparent, e.g. northeast of Burbanks or north of Coolgardie, major and minor isoclinal folds have repeated the stratigraphy. However, intense deformation, as in the Spargoville and Kunanalling regions, diminishes the thickness of the relatively incompetent komatiite. In shear zones, e.g. northwest Saddle Hills, thin ultramafic schists (*Au*) are derived from attenuated komatiite (Fig. 8).

Komatiites (*Aku*) forms extensive, thin to thick (5–30 m) flows which 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, grey shale horizon.

Metamorphosed komatiite is easily weathered and forms recessive units between ridges of basalt; outcrop is poor and consists of creek exposures, surface rubble,

Figure 8. Crenulation cleavage in ultramafic schist (*Au*) derived from komatiite, north-northwest of Comet Hill, Coolgardie.

and residual soil. However, the numerous costeans cut during the nickel boom provide reasonable exposure throughout the komatiite succession.

Rock type

Komatiites display a variety of textures and mineralogies which indicate their origin as extrusive rocks crystallized from an ultramafic 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, particularly 'spinifex textures' (Figs 9 and 10).

Pillow structures, 10–100 cm across, occur sporadically throughout the upper unit (*Aku*) and are locally abundant in the lower unit (*Akp*). Their forms are defined by narrow (2–10 mm), dark rinds of recrystal-lized glassy material and interstitial hyaloclastite. In a few localities, ocellar structures form close to the pillow margins. Within pillows the texture is commonly massive, but fine, random spinifex structures also form; this is well displayed in komatiite that outcrops along the eastern margin of the Saddle Hills.

North from Coolgardie, a lower subdivision (*Akp*) of the ultramafic succession is apparent. These rocks have a darker colour and spinifex textures are absent. They are massive and mottled in appearance due to an homogeneous granular platy texture. The metamorphic mineralogy is similar to the overlying ultramafic rocks and probably represents a peridotitic cumulate-textured rock.

In thin section, the metamorphosed komatiites have assemblages which typically correspond to peridotitic or pyroxenitic compositions. Tremolite–chlorite–talc–serpentine with minor magnetite, carbonate, and phlogopite is the common association, but there are localized occurrences of anthophyllite–chlorite–talc. Platy and plumose spinifex textures are well preserved in komatiite from 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 dunites is also preserved. The relative proportions of metamorphic minerals varies within a spinifex-textured sequence, e.g. talc predominates in dunitic basal cumulates.

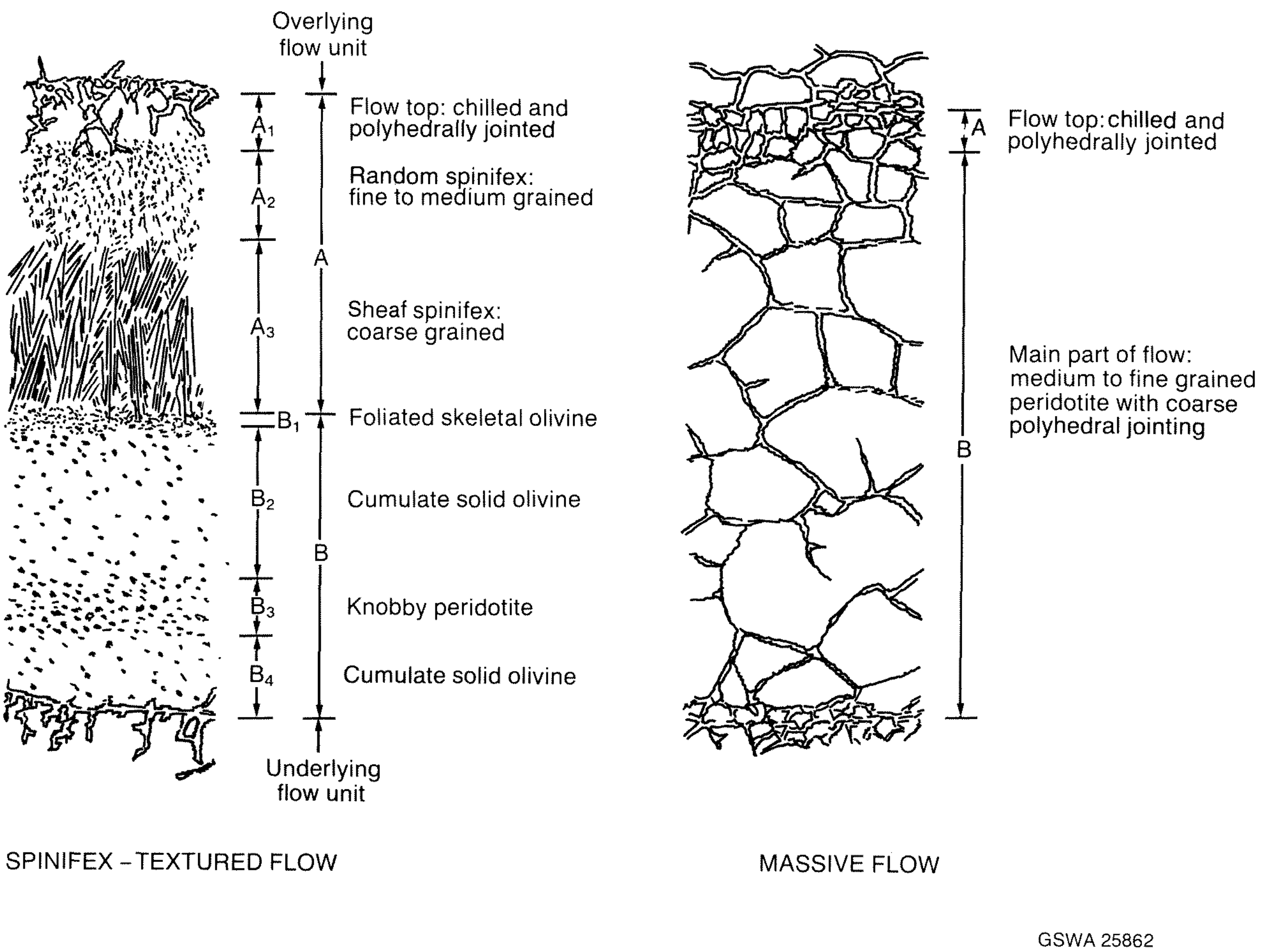


Figure 9. Textures within ultramafic lavas. The textural variation in each cooling unit is a function of the shapes and arrangements of olivine crystals. (After Ardnt et al., 1979)

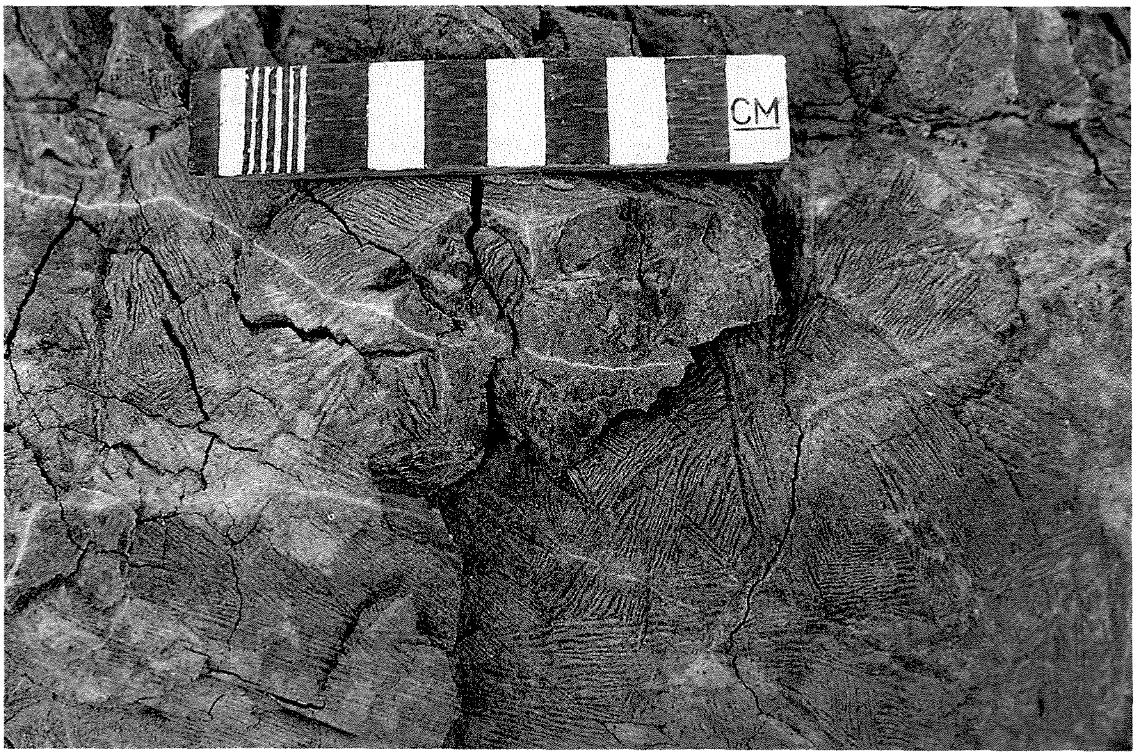


Figure 10A. Olivine spinifex texture in komatiite (*Aku*), northeast of Three Mile Hill, Coolgardie. Olivine forms randomly orientated books of bladed crystals which are coarser towards the centre of the flow.

Figure 10B. Olivine spinifex texture in komatiite (*Aku*), northeast of Three Mile Hill, Coolgardie. Olivine forms sheaves of bladed crystals which converge toward the top of the flow.

Metamorphism accompanying deformation has tended to obliterate igneous textures of the komatiites but trains of exsolved magnetite, which delineate original skeletal crystal forms, may be preserved. Spinifex-textured komatiites can be traced into strained zones, where there are progressive textural changes towards tremolite–talc schists. Oblate rosettes of tremolite nucleate at the boundaries of spinifex macrocrysts and are arranged in spaced bands parallel to foliation.

The growth of fine tremolite defining a crenulation cleavage post-dates the growth of coarse tremolite blades which pseudomorph spinifex macrocrysts. On the basis of textural relationships in komatiites from the Eastern Goldfields, Oliver et al. (1972) have deduced that olivine present in these rocks has a metamorphic origin.

Marker horizons

Sedimentary horizons

Located within the komatiite sequence are a number of horizons of shale, and one of basalt, which provide good evidence of bedding orientation and stratigraphic continuity. The shale beds are 1–5 m thick and laterally extensive. They are commonly graphitic or tuffaceous and may show internal compositional banding of quartz-rich and iron-rich layers, sometimes with tourmaline. Folding within the beds is due, in part, to soft-sediment slumping and, in part, to deformation during folding. Localized near-surface silicification of the shale has produced cherty horizons which are resistant to weathering.

Basaltic horizon

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 in the area and it is laterally very persistent. Multiple occurrences of it, located 5 km north-northeast of Burbanks, are interpreted as repetitions by isoclinal folding. Its contacts with the komatiite are sharp at the top and may be sharp or gradational at the bottom, whereas internal boundaries indicate that a number of flows are present. The grain size of the basalt varies both within and between localities, from medium to coarse and, locally, to very coarse; no chilled margins are apparent.

Although there are textural and compositional similarities between the basaltic rock in this horizon and high-Mg basalts, it contains darker, Fe-rich actinolite or hornblende, rather than the more Mg-rich amphibole. It is characterized by acicular (pyroxene) spinifex textures in the coarser units or stellate to plumose intergrowths of pyroxene and plagioclase in the finer units.

Discussion

Komatiite

Throughout KALGOORLIE and YILMIA, komatiite shows well developed spinifex-textured sequences, from granular cumulate bases through oriented, bladed megacrysts and random, fine bladed crystals to glassy flow-top breccias. Not all komatiite flows show the full textural sequence and there is some correlation between the extent of the sequence development and flow thickness, suggesting control by cooling rate. Structural attenuation of komatiites in high-strain zones (e.g. the southern Karramindie belt) indicates that stress was taken up in the cumulate layers at the base of flows where coarse spinifex-textured layers are isolated by narrow (5–50 cm) bands of talc schist.

The textural characteristics of komatiite flows are regionally consistent and provide valuable younging evidence where they are well preserved. The presence of skeletal spinifex textures together with granular cumulate textures is generally interpreted as a function of cooling rate differences within the flow (e.g. Arndt and Nisbet, 1982). The spinifex crystals were formed in a quench environment marginal to the flow whereas the cumulate crystals were formed by sedimentation of crystals nucleated within the flow core. In recent studies of komatiites north of Kalgoorlie, Hill et al. (1987) proposed that the degree of supercooling and the chemical composition of the magma control the generation of these textures: spinifex crystals form where there is fast nucleation and growth, whereas cumulates form where there is slow nucleation with growth.

The ultramafic rocks of the Eastern Goldfields were extensively examined for their nickel-bearing potential and there are many detailed descriptions of prospective areas. Good summaries at both regional and deposit scales are given by Groves and Lesher (1982) and Marston (1984). Descriptions of nickelliferous komatiites on YILMIA are given in the economic geology section of this report. No such deposits are known on KALGOORLIE.

Sedimentary marker horizons

The presence of sedimentary rocks within the komatiite pile indicates fluctuating conditions of volcanism and quiescence during extrusion. 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 material, and resulted in a 2–5 m thick heterogeneous horizon with relict textures and mineralogy of both lithologies. This association provides reliable evidence of younging.

Rare-earth element analyses of interflow sedimentary rocks from Kambalda (McLennan and Taylor, 1984) indicate the presence of some felsic volcanic material which must have been imported; this implies lateral diachronism in the stratigraphy or penecontemporaneous felsic and mafic volcanism. Both mechanisms are thought to have occurred on a regional scale.

Basaltic marker horizon

The origin of the basaltic marker horizon is problematical. It appears to be intimately related to the surrounding komatiites, and field and textural evidence indicate that it is extrusive; therefore, the maker horizon represents a modification in the chemistry or crystallization history of the komatiite magma. Differentiation of a magma batch prior to eruption may account for the greater iron and plagioclase contents. However, Campbell and Arndt (1982) have demonstrated that pyroxene spinifex textures can be generated by extreme supercooling of relatively MgO-rich liquids, and so the horizon may have been produced by temporarily unusual conditions of eruption.

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 marker horizon's upper contact with komatiite, particularly where it is intruded by one or more felsic porphyries, is a common location for gold deposits and, therefore, is a good exploration target. Figure 30 shows where gold occurrences are commonly found at this stratigraphic level.

Felsic volcaniclastic and sedimentary rocks (*Af, Afp, Aft, Afv, Asf*)

A complex succession of felsic volcanic, volcaniclastic, and intrusive rocks, with a maximum thickness of about 1500 m, occurs throughout KALGOORLIE and YILMIA. It overlies the sequence of komatiites with a sharp contact which is usually marked by a thin, grey shale horizon. The shale unit is overlain by intermediate volcaniclastic rock with an irregular and interfingering contact. Sandstone and conglomerate of the Kurrawang Formation appear to lie directly on felsic volcaniclastic rocks southeast of Seven Mile Hill.

These felsic rocks occur in broad, low-lying tracts between ridges formed by the mafic–ultramafic succession. Outcrop is generally poor and deeply lateritized but breakaway pediments and creek beds provide locally good, continuous exposure. The clastic rocks are now pale, clay-rich, soft rocks and much genetic interpretation has to be based on field observation rather than petrography. The intrusive rocks are harder and better exposed. In many of the larger breakaway, outcrops, local faulting and pervasive minor folding complicate apparent thicknesses.

The base of this sequence is marked by a 0.5–2 m thick grey shale overlain by felsic volcaniclastic rock (*Afv*) or tuff breccia (*Aft*). Northwest of Larkinville, thin beds of conglomerate with pebbles of mafic, ultramafic, and felsic rock occur at the base of the sequence. The finer rocks are generally thinly bedded (1–30 cm), purple, grey to white rocks with laterally extensive beds and range in grain size from mudstone to medium-grained sandstone. Coarser beds tend to be thicker, up to several metres, and less extensive. Individual beds may be homogeneous and featureless; however, graded beds and load structures are abundant and small-scale cross-stratification is present in places (Fig. 11).

Rock type

These felsic rocks are highly variable, so only broad subdivisions were possible. Distinction has been made between: subvolcanic intrusive dacite to rhyodacite porphyry (*Afp*); tuff-breccias (*Aft*) dominated by large, subangular cognate clasts; and other clastic rocks (*Afv, Asf*). The last division is the most complex as it incorporates the interbedded products of a number of volcanic and non-volcanic processes.

The dominant member of the volcaniclastic unit is ash-flow tuff in which proportions of lithic and vitric-crystal components vary both along and across strike (Fig. 12). Epiclastic sedimentary rocks are interbedded in variable proportions throughout the sequence but increase with distance from the occurrences of coarser pyroclastic and intrusive rocks.

Accretionary lapilli occur in 5–10 cm thick bands in the finer tuff horizons and are scattered throughout the sequence (Fig. 13). They are small (< 5 mm), pale, rounded structures often with concentric textural or compositional variations, and are usually scattered within a fine, tuffaceous matrix. They have nebulous boundaries with the host. The accretionary lapilli appear to have the same composition as their hosts, except for a slight excess of quartz.

Sedimentary structures, such as graded bedding, flame structures and drop-stone loading, are ubiquitous in the volcaniclastic rocks. Current structures, such as cross-bedding and ripple laminations, are more rare and confined to finer tuffs and ?epiclastic sedimentary rocks. Thin beds of polymictic pebbly sandstone or conglomerate, as well as lava flows, are rare in this unit.

Some thin to thick horizons of massive crystalline rocks located 3 km northwest of Kurrawang Lake and near Two Dams are interpreted as flows but they are of limited extent and poorly exposed.

Extensive grey shale units, up to 2 m thick, are present within the volcaniclastic sequence but it is not clear whether they were derived from primary, very fine ash deposits or chemical sediments, or whether they are secondary, epiclastic sedimentary rocks. One example, on the northwestern shores of White Flag Lake, shows lateral gradations between laminated ferruginous chert and carbonaceous grey shale (Fig. 14). Filamentous grains of carbonaceous material, which locally define conical forms, may be biogenic.

At the base of the tuff unit (*Aft*) is a series of coarse tuff breccias in which poorly sorted, subangular cognate blocks, up to 50 cm, are supported by a rhyodacitic matrix of crystal-lithic tuff (Fig. 15). Deformation has produced a preferred elongation (plunging steeply to the north), and some rounding, of clasts; however, angular or swallow-tail terminations of clasts are common. Variations within the clasts include differing concentrations and sizes of biotite, feldspar, or quartz phenocrysts; there are occasional ovoid clasts composed entirely of biotite or basalt–dolerite.

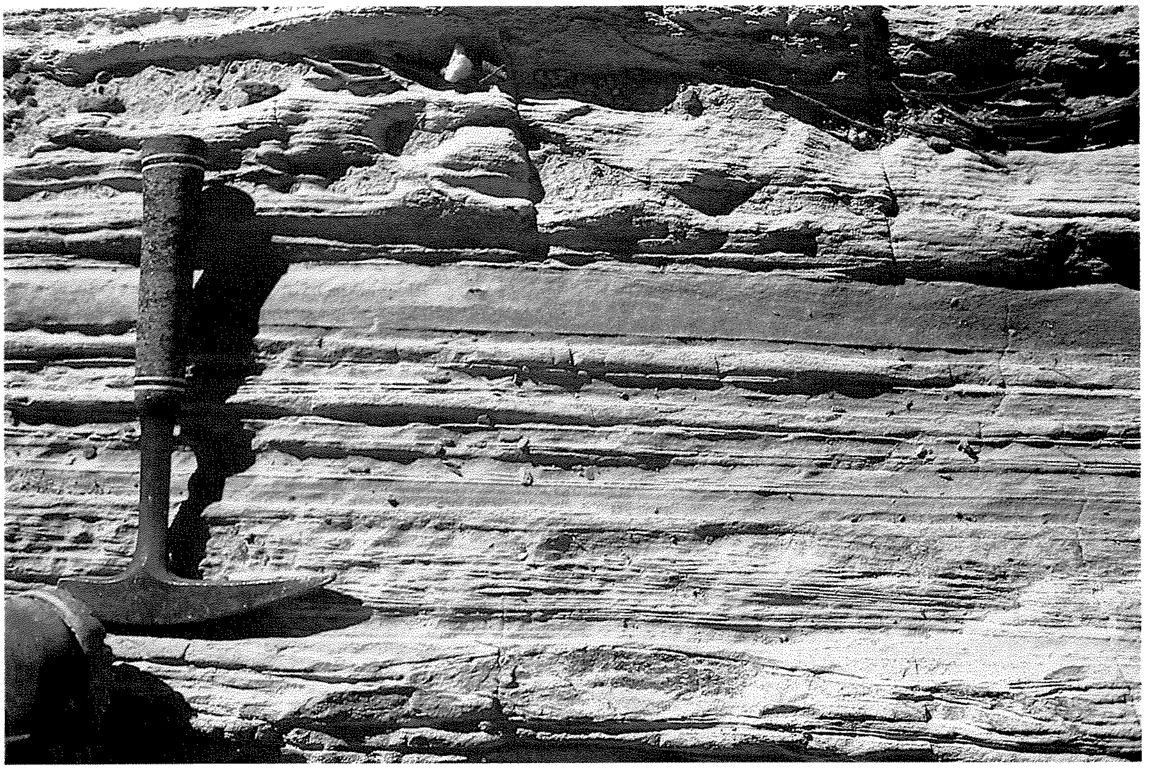


Figure 11. Thinly bedded, very fine-grained felsic volcaniclastic rocks (*Afv/Asf*), western end of Brown Lake, Coolgardie.

Figure 12. Felsic crystal tuff (*Afv*), east of Seven Mile Hill. Graded beds of bipyramidal quartz euhedra set in a very fine-grained felsic matrix.

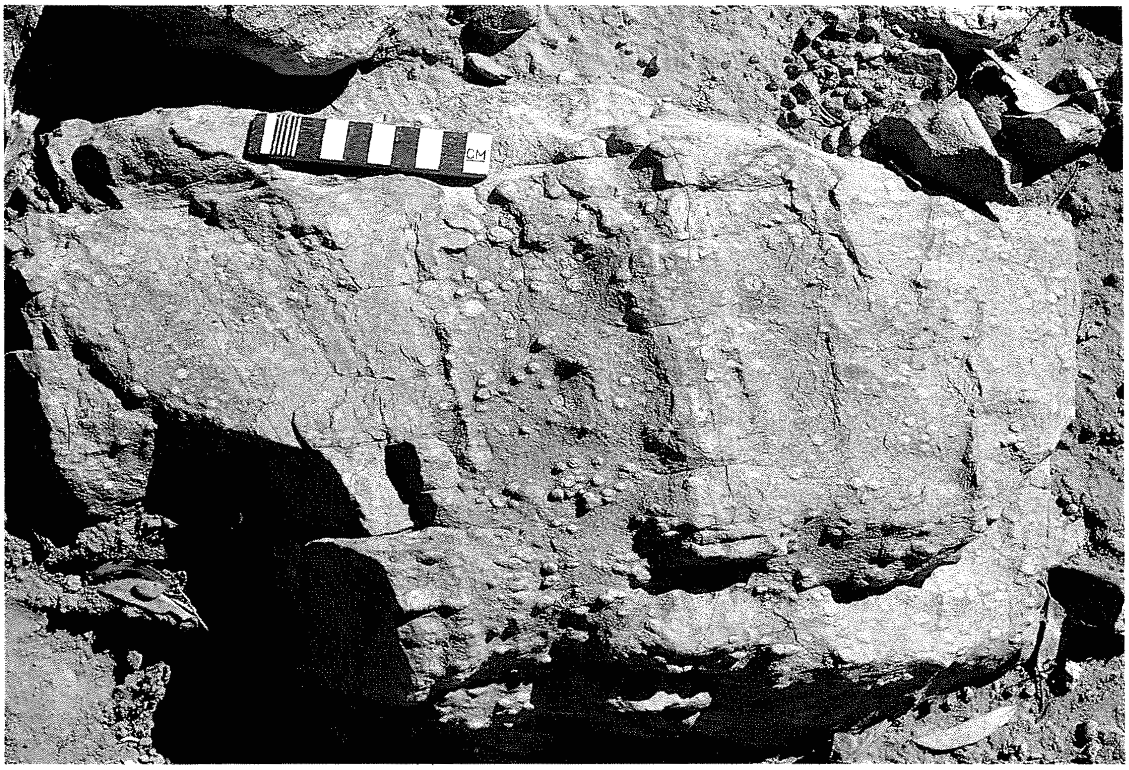
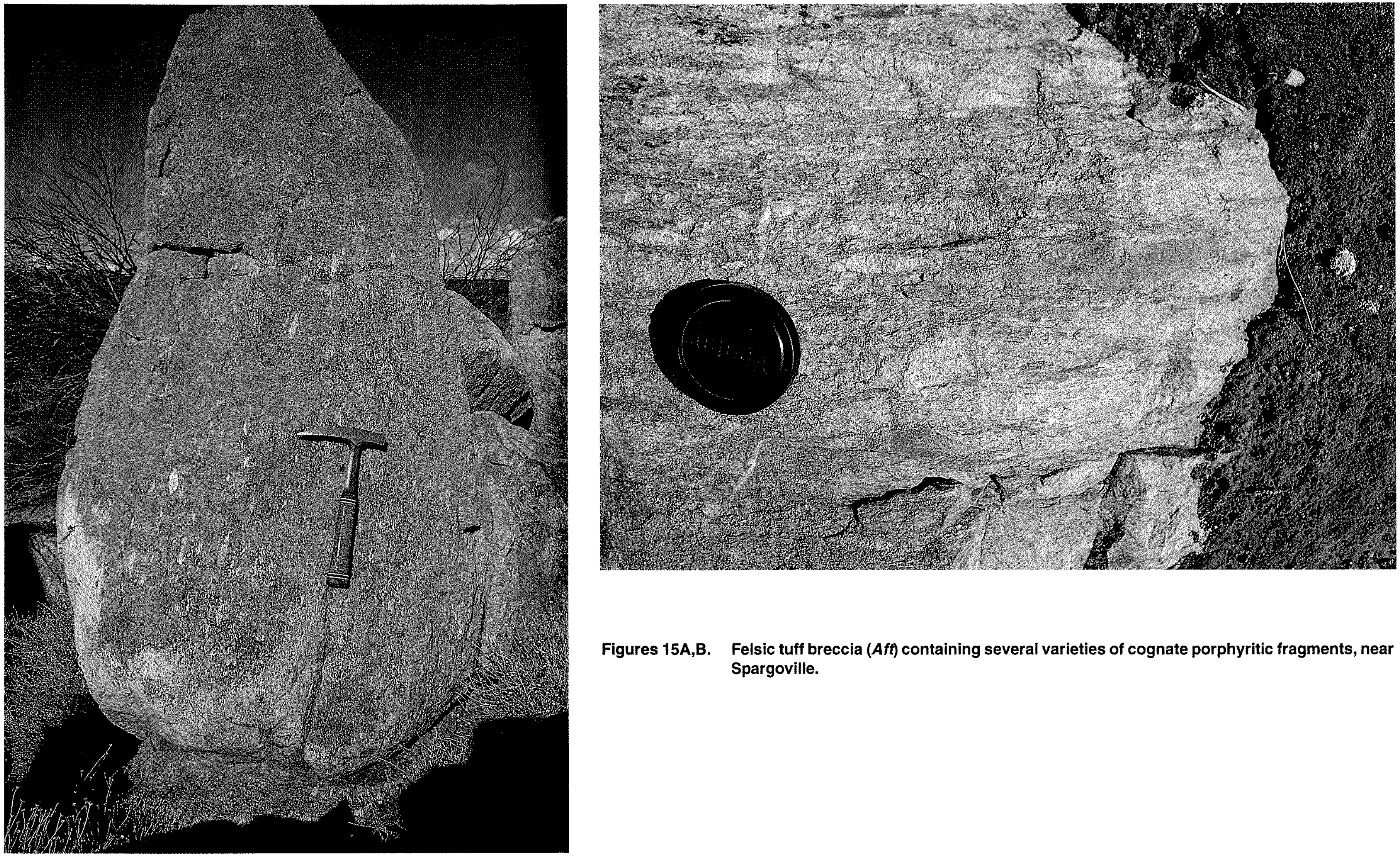


Figure 13. Accretionary lapilli in felsic volcaniclastic rock (*Afv*), south-southwest of Kundana.

Figure 14. Stromatic-banded carbonaceous chert and shale occurs as a thin, discontinuous horizon within felsic volcaniclastic rocks (*Afv*), northern end of White Flag Lake. Local textures indicate the carbon may be biogenic.



Figures 15A,B. **Felsic tuff breccia (*Aft*) containing several varieties of cognate porphyritic fragments, near Spargoville.**

The matrix is medium grained, leucocratic to mesocratic and has a variably granular texture; it contains up to 50% small (3 x 1 cm), ovoid lapilli (lithic clasts). Variation in mafic mineral content and orientation defines a banding aligned with the elongation of clasts. There is localized streaky banding accompanying a microcrystalline texture indicative of at least local devitrification of vitric-crystal tuff. The wrapping of matrix textures around larger clasts is common in the tuff breccia and has been interpreted as due to compaction or moderate welding of ash-flow tuff (Fehlberg and Giles, 1984), although some tectonic exaggeration is also evident. Marked reduction in clast size occurs along and across strike, and crystal tuffs dominate the facies transition. These tuffs comprise thinly bedded, fine- to medium-grained rocks with prominent subhedral quartz or feldspar phenocrysts.

In thin section, felsic volcaniclastic rocks are composed of variably comminuted fragments of porphyritic dacite to rhyodacite set in a matrix of similar lithic, crystal, and glassy fragments. Quartz, oligoclase, and lesser microcline occur as euhedral to subhedral phenocrysts in proportions which vary from horizon to horizon. The quartzo-feldspathic groundmass is generally microcrystalline and granular, and carries biotite and accessory apatite, sphene, zircon, and opaques. Middle greenschist to lower amphibolite facies metamorphism has variably recrystallized both groundmass and phenocrysts, and produced minor biotite, chlorite, sericite, and epidote.

Discussion

This section of the stratigraphy contains an heterogeneous variety of felsic volcaniclastic and intrusive rocks. The former range from proximal tuff breccias through more distal tuffs to interbedded tuffs and sedimentary rocks. The complexity of outcrop distribution is, in part, facies related and, in part, structurally controlled (Fig. 16). The concentration of proximal facies volcaniclastic and intrusive rocks in the Spargoville and east Saddle Hills areas indicates their proximity to volcanic centres and suggests some potential for mineralization.

Distinction between tuffs and epiclastic deposits is difficult to make as the products of metamorphism and weathering in both are similar in texture and mineralogy. The presence of cross-stratification is equivocally one of the few diagnostic field criteria which may distinguish epiclastic deposits from air-fall and subaqueous tuffaceous deposits. In thin section, the presence of abundant corroded quartz grains, some with preserved igneous embayments, has been used by Fehlberg and Giles (1984) as a criterion to identify epiclastic sedimentary rocks.

Depositional environment

The classification of this sequence of rocks has ranged between the extremes of 'purely sedimentary' (Kriewaldt, 1969; Glikson, 1971a) and 'volcanogenic' (Travis et al., 1971; Groves and Lesher, 1982). Whereas Gemuts and Theron (1975) incorporated each type into two different sequences. The lack of agreement arises from the paucity of outcrop, depth of weathering, and degree of metamorphic recrystallization of these rocks.

On KALGOORLIE and YILMIA it is clear that the coarser felsic fragmental rocks are hydroclastic or pyroclastic with subsequent deposition mainly into water. There are minor interbedded, mainly autochthonous, coarse sedimentary rocks. In the finer volcaniclastic rocks, the effects of metamorphism and weathering have been more effective in obliterating primary diagnostic textures. They ultimately become finely layered quartz–feldspar–lithia-mica rocks which are often mistakenly assumed to be primary, erosional sedimentary rocks.

The finer volcaniclastic rocks are interbedded with, and laterally gradational to, coarser tuffs, and only occur within the felsic volcanic terrain. The dominant sedimentary structures indicate deposition in standing water with subordinate fluvial deposition. Glikson's (1971a) geosynclinal model for the accumulation of these rocks required deposition in a deep-marine environment but common occurrences of accretionary lapilli indicate dominantly shallow-water deposition. These features, together with comparisons of other felsic volcanic terranes (Fisher and Schmincke, 1984), suggest that many of the finer volcaniclastic rocks are distal pyroclastic deposits and reworked tuffs. They are interbedded with lesser, mainly autochthonous, sedimentary rocks.

Timing of deposition

Several radiometric age determinations (Compston and Turek, 1973) constrain the minimum age of extrusion of the volcaniclastic rocks but none is available for a maximum age.

Porphyry pebbles from the conglomerate in the overlying Kurrawang Formation are inferred to have been derived from the felsic and intermediate volcaniclastic rocks; Rb–Sr data from metamorphic biotite in the Kurrawang Formation, thereby, gives a gross minimum age of 2550 Ma to the volcaniclastic rocks. A conservative estimate of their age was given as 'older than 2670 Ma'. A more specific minimum age of 2620 ± 20 Ma was given by Rb–Sr data from mineral and whole-rock samples of the Mungari Monzogranite which intrudes the volcaniclastic rocks.

Felsic schist (*Afs*)

Schistose felsic rocks are present throughout the succession but occur more commonly in association with grey shale interflow units. They are mainly thin (< 2 m) units which may be only 5–10 mm thick locally. Most schists are concordant and may occur as a group of thin, parallel horizons or as a single homogeneous unit.

Felsic schist has a microgranular matrix draped around augen of relict, subhedral phenocrysts of plagioclase and quartz. The matrix comprises quartz and feldspar grains elongated parallel to biotite and white mica; amphibole is present in some samples.

These schists are compositionally similar to the suite of felsic volcanic and volcaniclastic rocks. Discordant varieties are clearly derived from intrusive porphyries but concordant varieties are more difficult to assign. It is inferred, therefore, that they may be the products of metamorphism and/or tectonism of a variety of felsic volcanic and volcaniclastic rocks.

Andalusite schist (*Afsa*)

Pelitic schist rich in andalusite megacrysts occurs as a 250 x 6000 m unit located 4 km southwest of Mungari. The unit forms a prominent ridge trending 135° which is discordant to the local bedding and structural trends. It is flanked to the east and west by felsic volcaniclastic rocks and dolerite, and to the north by the Mungari Monzogranite.

The schist is rich in biotite which locally reaches a grain size of 2 mm across, defines foliation, and imparts a dark overall coloration to the rock. Large (< 5 cm) pink, prismatic andalusite (chiastolite) euhedra are scattered throughout, subparallel to foliation in the schist. Some andalusite megacrysts show fracturing and brittle offsets, apparently due to shearing parallel to schistosity; others are truncated at the margin of the unit.

In thin section, the rock reveals a complex metamorphic and deformational history. The foliated groundmass is composed of fine-grained granular quartz with biotite and accessory opaques and tourmaline, and supports large andalusite euhedra which are cross-fractured, offset, and locally pinitized. Fractures persist

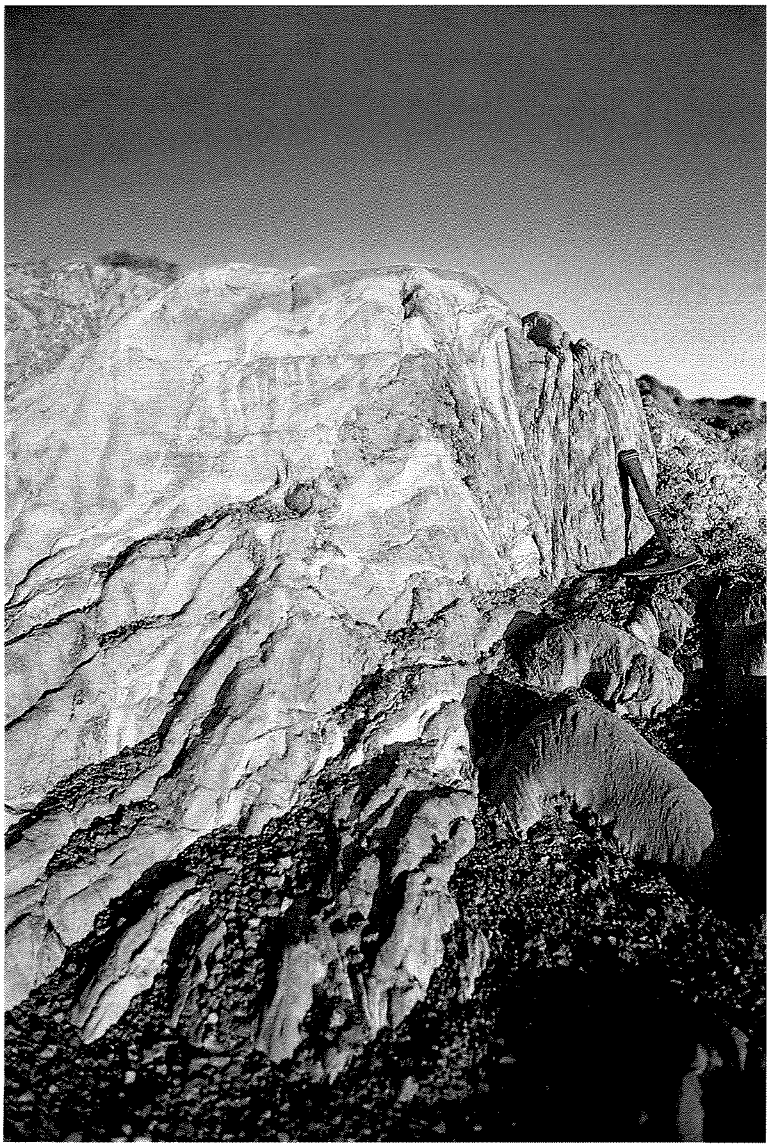


Figure 16. Minor folding in felsic volcaniclastic rocks (*Af*), northeast of Mount Marion, showing preferrential attenuation of east limbs.

through the groundmass as spaced stringers of microgranulated quartz and entrained micas. Coarse (< 2 mm), equant, sieved plates of biotite grow across the andalusite and some of the fractures, but are themselves locally truncated.

The adjacent volcaniclastic and intrusive rocks appear to be at a generally lower metamorphic grade but there are pelitic and psammitic rocks of similar grade located 2.5 km southeast of Perron Dam. These rocks have an upright foliation which increases in intensity westward, towards a north–south fault.

The ridge of andalusite schist is a tectonic horizon which is discordant to the local stratigraphy. It was derived from felsic volcaniclastic and volcanic rocks which were thermally metamorphosed close to the margin of the Mungari Monzogranite. This pluton probably extends at least as far southeast as the eastern end of Brown Lake. Shearing or faulting generated the schist and subsequent intermittent movement juxtaposed the tectonized hornfelses against their lower grade equivalents. Initial movement may have been related to granitoid emplacement but later shearing related to the adjacent Kunanalling Shear Zone was dominant. The metamorphosed clastic rocks southeast of Perron Dam are equivalent hornfelses which have escaped intense shearing.

Intermediate volcaniclastic rock (*Aiv*)

Intermediate volcaniclastic rocks have been recognized in three northwest-trending zones across central KALGOORLIE but are not known on YILMIA. They are best exposed in a 19 km zone from White Flag Lake to Laurie Dam in which they reach a maximum thickness of about 1500 m. Thinner zones, each with intermittent exposure over 8 km, occur from Kundana to Blue Funnel and from Red Lake towards Kurrawang Mission.

These zones of intermediate volcanic rock overlie and are locally interbedded with felsic volcaniclastic rocks (*Afv*). The contact appears to be conformable north of Twenty-Seven Dam, but it is obscured by the intrusion of a thin dolerite sill elsewhere. An erosional disconformity separates the intermediate volcaniclastic rocks from the overlying Kurrawang Formation.

The sequence of intermediate volcaniclastic rocks is dominated by pyroclastic lithologies with minor flow and intrusive rocks. However, no distinction between lithotypes has been made at 1:100 000 scale of mapping.

Rock types

Tuff breccia is the most abundant intermediate rock type present, comprising 80–90% of the unit (Fig. 17a). It forms thickly bedded deposits of variable, but moderate, lateral extent. Clasts are angular to subrounded, up to 50 cm in size, and have a subhorizontal elongation parallel to cleavage. The clasts are poorly sorted at outcrop scale but there is a general upward decrease in average clast size within each horizon. There is a unsystematic mixture of matrix- and clast-supported tuff and, in some cases, the matrix is absent altogether. The rocks have an overall green or grey-green colour and weathered surfaces are characterized by millimetre-sized rhombic pits resulted from erosion of carbonate crystals.

Clasts are composed of a variety of intermediate volcanic and subvolcanic rock types, many of which contain cognate fragments. The most abundant types are fine-grained to cryptocrystalline lavas and tuffs, which are rich in plagioclase and pyroxene phenocrysts. Small bulbous vesicles are filled with quartz and/or carbonate. Streaky laminations in finer-grained rocks are interpreted as relict viscous-flow textures. Scattered clasts of medium-grained, homogeneous rock with acicular amphiboles represent subvolcanic intrusive deposits. Also present in the tuff breccia are scattered fragments of accretionary lapilli tuff, and lithic and crystal tuffs along with rare fragments of gabbro.

The fine- to coarse-grained matrix of the tuff breccia is very immature, poorly sorted, and shows no bedding lamination. It is compositionally similar to the clasts it supports, comprising lithic fragments and phenocrysts of plagioclase and pyroxene set in devitrified glass with microlitic feldspar and chlorite. Vugs and amygdaloidal quartz and carbonate are locally abundant in the matrix.

Interbedded with coarser tuff breccias are thinly bedded (5–10 cm) lapilli tuffs (Fig. 17b), crystal tuffs, and laminated, very fine-grained ash deposits (Fig. 17c) which are commonly graded. Some horizons of finer bedded tuffs show shallow, trough cross-bedding, indicating that at least some subaqueous deposition has occurred. The presence of rare, thin beds of accretionary lapilli tuff support this interpretation.

Lavas are difficult to identify in this region; however, fine-grained to cryptocrystalline rocks with streaky banding which contain scattered feldspar phenocrysts and vuggy quartz are interpreted as lava flows. They are rare but always accompanied by minor interflow, fine volcaniclastic or epiclastic sedimentary rocks.

All these volcaniclastic rocks are varieties of porphyritic and amygdaloidal andesite. Euhedral phenocrysts of plagioclase and pyroxene, up to 5 mm in length, occupy 25–30% of the rock; they are usually twinned and may show relict zoning. Primary amphibole phenocrysts are scarce. Plagioclase has been altered to albite and is commonly sieved with sericite and epidote (-carbonate). Pyroxene has been partly or totally pseudomorphed by uralite which is locally accompanied by epidote and carbonate. The groundmass comprises granular epidote, albite, chlorite, and carbonate with fine acicular actinolite. Vesicles, which may occupy 15% of the rock, are filled with chalcedonic quartz or carbonate which commonly form as a single crystal and may be zoned. Some vesicles are rimmed by chlorite and epidote. Turbid, devitrified glass is common in the matrix of vitrophyric flows but is only a minor constituent in most other rocks.

Discussion

The abundance and thickness of cognate fragmental rocks indicate that the andesitic unit (*Aiv*) is dominated by tuffs and tuff breccias rather than flow-top breccias which, although present, are limited in extent and thickness.

The tuff breccias with coarsest average and maximum clast sizes occur west of White Flag Lake along with the few recognized flow rocks. Average clast size shows a gradual decrease away from this area. This regional concentration of coarser tuffs and flows is attributed to the presence of an andesitic volcanic centre in the vicinity of White Flag Lake.

Exposures of thick sequences close to the volcanic centre show repeated upward gradation from massive coarse breccias, through lapilli tuffs, to finely laminated ash deposits. Each of these graded horizons is interpreted as an individual eruptive event. The fragments were derived from pre-erupted material, within or close to the volcanic edifice, and mixed with juvenile magmatic components.

There is a general lack of fine-scale grading and cross-bedding, and a unsystematic absence of matrix between the coarser clasts of some horizons. These features are indicative of air-fall deposition of non-welded or cold pyroclastic flows. Thin horizons of accretionary lapilli tuffs and cross-bedded fine tuffs interbedded with tuff breccias on the White Flag Lake peninsula are shallow-water deposits characteristic of ash-cloud or basal-surge deposits in shallow lakes close to a volcanic centre (Fisher and Schmincke, 1984).

East of Blue Dam, more distal andesitic tuffs are represented by numerous cyclic alternations of thin- to medium-bedded tuffs and very fine-grained ash deposits. Graded bedding in the tuff is well preserved and coarser basal deposits contain fragments derived from the finer substratum. These rocks are interpreted as distal portions of ash-flow tuffs deposited in standing water with possible local reworking.

Timing of deposition

There is a close spatial relationship between the intermediate and felsic volcaniclastic rocks within an apparently conformable succession. Compston and Turek (1973) have used Rb–Sr isotopic data to constrain the time of deposition of the overlying Kurrawang Formation (> 2550 Ma) and establish a general age for the underlying felsic volcanic rocks (> 2670 Ma). The andesitic rocks were probably penecontemporaneous with the felsic volcanic episode and their age of eruption closer to the older isotopic age. The timing of the erosional hiatus before the deposition of the Kurrawang Formation is unknown.

Metamorphism and structure

The metamorphic mineral assemblage present in these rocks and their degree of recrystallization indicates

Figure 17A. Intermediate volcaniclastic rocks (*Aiv*), White Flag Lake, occur as graded horizons from tuff breccia (Fig.17A), through coarse lapilli tuff (Fig. 17B), to fine lapilli tuff (Fig. 17C).

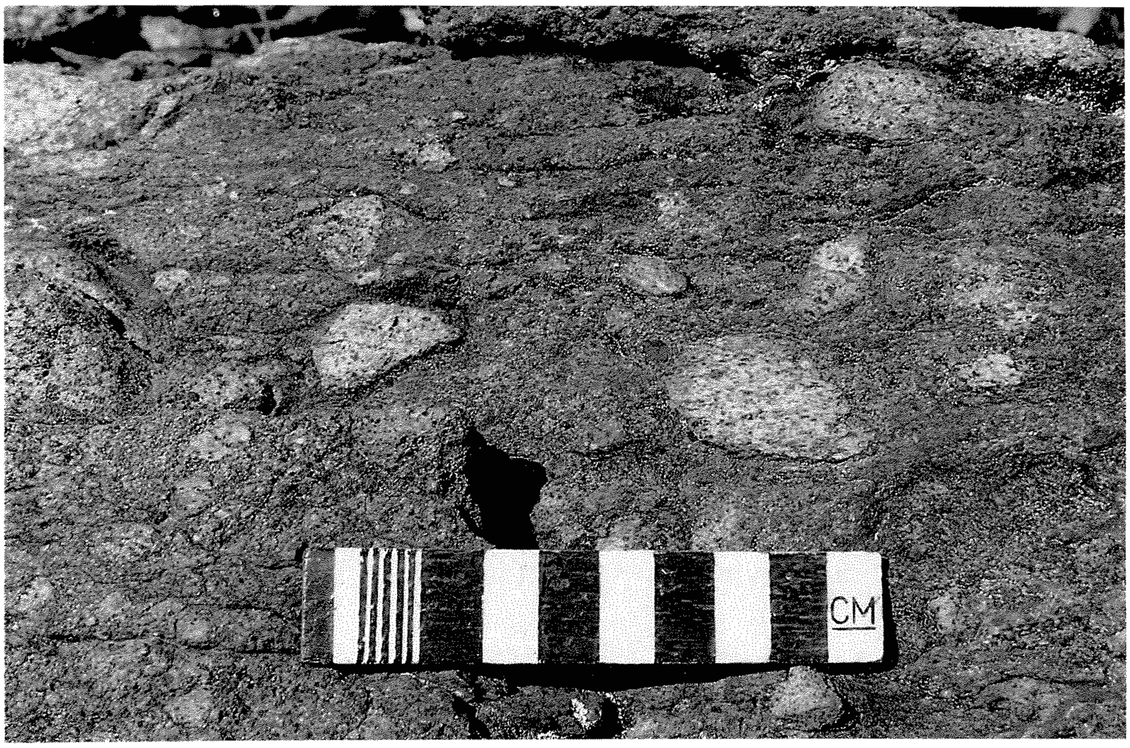


Figure 17B. Horizons of coarse lappilli tuff (*Aiv*), White Flag Lake.

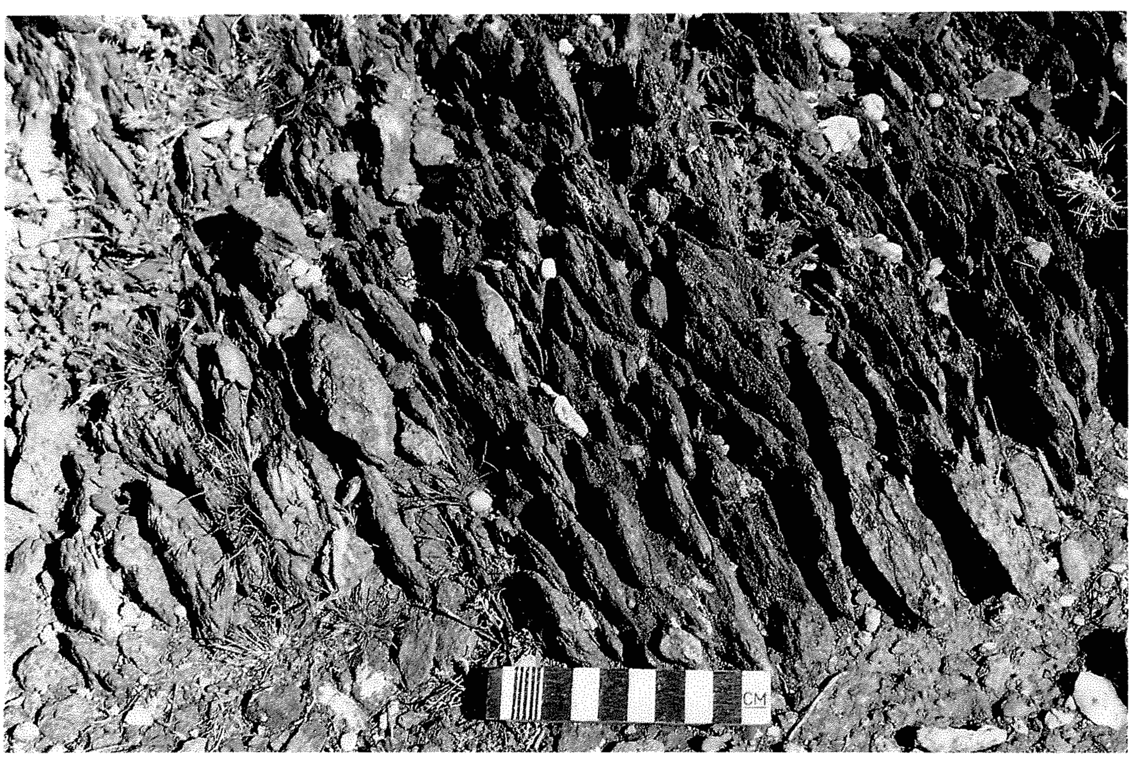


Figure 17C. Horizons of fine lappilli tuff (*Aiv*), White Flag Lake general attainment of middle to upper greenschist facies conditions.

Consistent younging evidence reveals that the White Flag Lake belt and the two narrower belts to the west and south are complementary limbs of the Kurrawang Syncline. Their relative thicknesses are a primary feature of facies variation, with some tectonic thinning apparent east of Blue Dam.

A moderate to strong, upright cleavage, which is axial planar to this open fold, is manifest in the finer tuffs as a well developed, anastomosing foliation. In the coarser tuffs it is mainly confined to the matrix where it accentuates clast outlines. The distinct elongation and common orientation of clasts is a further result of the deformation and not of primary deposition.

Kurrawang Formation *(Ask, Asa)*

The Kurrawang Formation, formerly 'Kurrawang Beds', occurs in a 5 x 50 km zone which has a northwesterly trend across KALGOORLIE, but it is not known on YILMIA. The unit, which has a maximum total thickness of 2000 m, occupies an open-style syncline with a shallow northwesterly plunge.

The Kurrawang Formation lies with apparent disconformity on felsic and intermediate volcaniclastic rocks. There is an erosional base and localized palaeocolluvial deposits, but bedding orientation is generally conformable with the substrata. The top of the Kurrawang Formation is not exposed on KALGOORLIE.

Two sub-units have been mapped in the Kurrawang Formation, a lower polymictic conglomerate (*Ask*) succeeded, with gradational contact, by an upper sandstone (*Asa*).

Rock types

Conglomerate *(Ask)*

The lower division *(Ask)* of the Kurrawang Formation comprises cobble conglomerate, sandy pebble conglomerate, and pebbly sandstone (Figs 18A, 18B). The sub-unit has a maximum thickness of 750 m at White Lake and gradually thins to the northwest. In the north it is thicker on the western limb of the syncline than it is on the eastern limb.

The conglomerate is poorly sorted, matrix supported and occurs in massive, medium to thick beds. There are common lenticular intercalations of pebbly, coarse sandstone and minor fine sandstone.

Clasts in the conglomerate have a maximum size of 25 cm and an average size in the range of 5 to 10 cm. They are well rounded and ellipsoidal, and have a consistently subhorizontal elongation. Clasts of banded iron-formation (BIF) tend to be more tabular but are also well rounded. Where clasts are in contact, interlocking embayment structures are commonly seen; no imbrication of clasts has been recognized.

A summary of clast types and their characteristics is given in Table 1. The most abundant type is felsic to intermediate rock, which is derived from a variety of volcanic and subvolcanic intrusive deposits. Clasts of banded iron-formation, chert, and quartzite (some of it fuchsitic) occur sporadically, and there are rare, small clasts of amphibolite, basalt, and ultramafic rock types. There is no systematic distribution of clast size or type on a regional basis, with the exception of abundant banded iron-formation clasts which are confined to an extensive, 30 m thick horizon on KALGOORLIE.

The matrix of the conglomerate is a grey to khaki, medium- to coarse-grained sandstone or, rarely, siltstone. It is immature, poorly sorted and is similar in composition to the interbedded sandstones. The deformed matrix exhibits a wrap-around texture to clasts at all scales, and 'feathering' of matrix and clasts occurs at pressure-shadow terminations. In the matrix there is a predominance of subangular lithic grains accompanied by quartz and feldspar. The lithic grains have compositions similar to those of the megaclasts. Metamorphic biotite is abundant and constitutes a distinct, anastomosing foliation. Other minerals present in the matrix include chlorite, epidote, euhedral magnetite, zircon, and rare tourmaline.

Sandstone *(Asa)*

There is a gradational zone, up to 20 m thick, between the lower conglomerate and the dominant upper sandstone in which cobble horizons and pebble–cobble lags are common in lenticular-bedded, pebbly sandstone. The sandstone (*Asa*) overlies the conglomerate throughout KALGOORLIE and has a maximum thickness of 1300 m. It is thin- to medium-bedded, and beds are mainly lenticular with low sinuosity. Trough cross-bedding and grading within beds are commonly seen in the sandstone.

The sandstone sub-unit is composed predominantly of a medium- to coarse-grained, granular or pebbly sandstone in the lower part of the sequence and grades upwards, unsystematically, to a generally finer sandstone and siltstone. However, finer sedimentary rocks are sparsely intercalated at all levels.

Pebble-sized clasts are well rounded, subspherical, and comprise felsic volcanic rock, quartzite, siltstone, and granitoid rock. The sandstone is moderately to well sorted, but immature, and contains subangular to subrounded detritus. Fragments of felsic volcanic rocks, quartzite, siltstone, and shale constitute the dominant lithic clast population. They are accompanied by clastic plagioclase and minor K-feldspar, both of which are sericitized. In both the clasts and the matrix, metamorphic biotite, white mica, and opaques are abundant and are associated with epidote, chlorite, and albite. Quartz exhibits complex grain-boundary recrystallization.

Figure 18A. Kurrawang Formation (*Ask*), at Lake Douglas, containing well rounded clasts of granitoid rock, porphyry, quartzite, and iron-banded chert. Cleavage and elongation of pebbles is oblique to bedding, shown by a thin sandstone bed.

Figure 18B. A close-up view of the Kurrawang Formation (*Ask*) at Lake Douglas, showing the wrap-around texture of matrix against clasts, impact-dissolution features of clasts in contact, and pre-deposition veining of Fe-chert clasts.

Table 1. Features of conglomerate clasts in the Kurrawang Formation

Type	*Shape*	*Distribution*	*Grain size*	*Composition*	*Texture*	*Comments*
Banded iron-formation	Tabloid, subrounded	Abundant but confined to a 30 m horizon	Very fine grained	Cherty iron-formation; up to 25% euhedral magnetite; with quartz, minor carbonate and chlorite	Microgranoblastic	Banding may be oblique to flat faces of clasts; these are probably jointed fragments. Some have ?folds and quartz veining, implying they were deformed prior to incorporation in the conglomerate.
Felsic volcanic	Prolate, rounded	Ubiquitous	Fine to medium grained	Rhyolite to dacite as feldspar (–quartz) porphyries. Plagioclase commonly replaced by albite and sericite; quartz is recrystallized; biotite pseudomorphs amphibole; accessory chlorite, opaques, epidote, apatite, and zircon	Complex recrystallization	Textures indicate a variety of lithofacies are represented, from high-level intrusives to flows and tuffs. Some pebbles give a Rb–Sr isochron age of 2670 ± 255 Ma (Compston and Turk, 1973).
Quartzite	Prolate, rounded	Abundant	Fine to medium grained	Quartzite. 5–6% white mica and local fuchsite, acessory zircon and tourmaline	Granoblastic, polygonal	Texture and grain size suggest that recrystallization at amphibole facies occurred prior to incorporation in the conglomerate.
Granitoid	Spherical, rounded	Scattered	Medium to coarse grained	Granodiorite, monzogranite	Recrystallized, hypidiomorphic	Several granitoid types are represented, from gneiss to plutonic varieties. Some pebbles give a Rb–Sr isochron age of 2885 ± 165 Ma (Compston and Turek, 1973).
Mafic–ultramafic	Discoid, rounded	Rare	Fine to medium grained	Mafic to ultramafic rock. Amphibole, chlorite(–biotite) with accessory quartz and opaques	Schistose	These appear to be small fragments of metabasalt, metakomatiite, and biotite schist. Schistosity predates incorporation in the conglomerate.

Discussion

Sedimentology

The sedimentology of the Kurrawang Formation indicates that deposition began in a fluctuating high-energy, proximal environment, which waned with time. The conglomerate and conglomeratic sandstone are interpreted as having formed in a stream-dominated, alluvial fan system (Bull, 1972). The thicker conglomerate horizons probably represent debris-flow deposition, whereas the thinner and discontinuous horizons represent lag deposits in alluvial channels. The succeeding sandstones show progressively greater sorting and grading, and may represent distal facies of the alluvial fan system. Alternatively, the distal environment may have been subaqueous with the fan prograding to a braided-river system or fan delta.

The exposure of the Kurrawang Formation is parallel to apparently long lived wrench-fault systems which may have developed strike-slip or transtensional basins (Mitchell and Reading, 1986; Ramsay and Huber, 1987). The unsystematic clast size and type distribution may then be attributed to rejuvenation as block subsidence extended the basin margins (Mitchell and Reading, 1986).

Provenance

The variety of lithologies occurring as clasts in the Kurrawang Formation indicates a complex provenance. However, the overall preponderance of felsic to intermediate volcanic clasts indicates that the major source of detritus is the underlying felsic and intermediate volcanic terrain.

The banded iron-formation clasts have been regarded as enigmatic (Glikson, 1971b; Groves and Gee, 1980) due to the apparent paucity of suitable source rocks in the vicinity. Banded iron-formation has now been mapped 60 km to the southwest at Queen Victoria Rock (120°55', 31°20'S) (Hunter, 1989) and 100 km to the northwest at Callion (Kriewaldt, 1969). There is a strong aeromagnetic signature which passes west of Bullabulling (Aerodata, 1983) and links these localities, indicating that a proximal source for the clasts possibly did exist. On the basis of thirty cross-bed measurements in the sandstone sub-unit, Glikson (1971b) deduced a general east to southeast palaeocurrent orientation which is consistent with a western source for the iron-formation clasts.

Timing of deposition

The timing of deposition of the Kurrawang Formation in relation to greenstone belt evolution is contentious. Glikson (1971b) claimed that deposition predated the intrusion of the Mungari Monzogranite as its contact aureole overprints a tectonic fabric in rocks underlying the Kurrawang Formation. Such a deduction remains equivocal. Isotopic age determinations by Compston and Turek (1973) placed some constraints on the provenance and deposition of the Kurrawang clasts by suggesting that the felsic volcanic and granitoid source rocks were at least 2670 Ma old. A complementary younger limit for the age of deposition of the conglomerate was established at 2550 Ma by a Rb–Sr age on a metamorphic biotite from the matrix of the conglomerate. Whole-rock and mineral age data gave the age of emplacement of the Mungari pluton as 2620 ± 20 Ma.

Gemuts and Theron (1975) placed the Kurrawang Formation at the top of their multicyclic sequential stratigraphy and placed the lithologically similar 'Merougil beds' (McCall, 1969) at the top of their lower cycle. Griffin et al. (1983) correlated the Kurrawang Formation and 'Merougil beds' at the top of the regional succession in their proposal for a single-sequence stratigraphy.

Some clasts in the conglomerate have a schistosity, while others are folded or quartz veined. These features suggest that some source rocks had been deformed prior to erosion and deposition in the conglomerate. However, the extent of regional deformation prior to opening of the Kurrawang basin is unclear.

Thin, discontinuous deposits of sandstone and siltstone underlying the conglomerate are interpreted as palaeocolluvial deposits on an irregular erosion surface in the underlying felsic and intermediate rocks. At White Flag Lake, the conglomerate has an erosional base which rests directly on intermediate tuffs. The orientation of bedding in the Kurrawang Formation is subparallel to the substrata throughout KALGOORLIE, and no angular unconformities are known.

Detailed aeromagnetic data reveals converging trends of concealed rocks 2 km north of the Kurrawang Mission. This was cited by Glikson (1971b) as evidence for an (angular) unconformity between the Kurrawang Formation and the underlying volcaniclastic rocks but without any outcrop as confirmation. The moderately magnetic unit converging with the trend of the Kurrawang Formation is, here, inferred to be a dolerite which intrudes upper levels of the volcaniclastic pile and is exposed 3 km south-southeast of the mission. Thus, the convergence may be a manifestation of a discordant intrusion, but this is not consistent with the regional concordance of most dolerites on KALGOORLIE and YILMIA. A major tectonic lineament which lies to the west of the Kurrawang Syncline, and extends from Blue Funnel through Kundana to Red Lake, has juxtaposed the Kurrawang Formation with various units interpreted to be lower in the succession. Faulting associated with this lineament is probably responsible for the convergence cited as north of the mission.

Metamorphism and structure

The metamorphic mineral assemblage and degree of recrystallization of the Kurrawang Formation is uniform throughout the unit and indicates general attainment of middle to upper greenschist facies conditions.

In the Kurrawang Formation a moderately strong, northwest-trending cleavage is manifest in oriented growth of phyllosilicates. This fabric anastomoses more competent clasts at all scales but is strongest in the more mica-rich conglomerate and fine-grained sandstone. The dominant cleavage is axial planar to the open-style synclinal fold but a perpendicular crenulation cleavage is apparent north of Kundana.

Interlocking embayment structures in touching cobbles are considered to be the result of stress-related, pressure solution processes. Glikson (1971) deduced that the ellipsoidal shape of some pebbles and cobbles represented a 50% flattening in the cleavage plane. That analysis did not take account of any inherent elongation of the clasts or any possible mechanical rotation in the matrix and so the value is likely to be excessive. By applying Borradaile's (1984) method for determining strain in pebbles with a pre-existing planar structure, and assuming passive strain, a value for flattening of nearer 30% is obtained. However, there is incipient stretching and brittle fracturing in some pebbles which indicates that a lateral component of shear has affected these rocks.

Archaean mafic intrusive rocks (*Ao, Aog, Aod, Aol*)

Mafic intrusive rocks (*Ao, Aog, Aod, Aol*) with doleritic or gabbroic affinity occur throughout KALGOORLIE and YILMIA, and are found mainly within basalt. They form thick intrusive sills (detailed below) as well as thinner undivided units (*Ao*) and their deformed equivalents (*Ao*).

Three Mile Sill

The Three Mile Sill is a thick (500–800 m) layered gabbro complex *(Aog)* which occurs throughout KALGOORLIE and YILMIA, and intrudes lower portions of the sequence of high-Mg basalts *(Abm)*. The sill is never prominently transgressive, except in the Saddle Hills and Karramindie belts where sharp transgressions are evident.

The upper contact of the Three Mile Sill is invariably concordant but the sill margin is commonly interleaved with wallrock. Long (> 10 m), thin (up to 1 m) screens of basalt or interflow shale horizons commonly occur up to 10 m within the intrusion. The lower margin of the sill is more variable in character and is poorly exposed.

Within the gabbro complex, gradation occurs between coarse-grained, melanocratic pyroxenite and leucocratic (quartzo-)feldspathic horizons that contain scattered bladed pyroxenes. This variation is interpreted as crystal differentiation and is used to determine younging. The leucogabbro varies in grain size from fine to very coarse, probably as a result of the concentration of volatiles during crystallization.

Repetition of the compositional layering occurs on a broad scale, with two or three cycles being 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 may indicate some tectonic repetition has occurred.

Figure 19. Typical massive gabbro (*Aog*), Three Mile Sill, at Logans Find.

The gabbro (*Aog*) is generally massive or weakly foliated (Fig. 19) but is locally strongly foliated. The deformation is commonly confined to zones, up to 2 m wide, of amphibole schists which correspond to competency contrasts at the boundaries between layers. In zones of tight folding (e.g. east of Burbanks siding), there is general, but heterogeneous, development of foliation resulting in a streaky amphibolite with broadly anastomosing schistosity of varying intensity.

There are vertical and lateral variations from ophitic to intergranular textures, the former being predominant in coarser horizons and producing a characteristic mottled appearance. Original platy pyroxenes are replaced by single or matted amphibole crystals which invariably define a strong, upright lineation. In thin section, samples from areas of low strain exhibit good preservation of igneous textures, and original large (< 10 mm), equant, subophitic to ophitic plates of pyroxene, enclosing blades of plagioclase, persist.

Compositionally, the sill ranges from a basal coarse-grained, melanocratic pyroxenite, containing some plagioclase, to a medium-grained, mesocratic to leucocratic, gabbroic-textured top. Upper marginal zones may be chilled or coarse grained and more mafic, indicating the presence of inward, as well as upward, differentiation.

In the gabbro, low to middle amphibolite facies metamorphism has produced randomly oriented, single-crystal amphibole pseudomorphs after pyroxene plates. Amphibole varies unsystematically throughout the area from a pale-green actinolitic variety to an olive-green hornblendic variety. Granoblastic recrystallization of plagioclase has produced coarse mosaics of andesine with polygonal to interlobate forms which are confined within the bladed forms of the protocrysts. Other minerals present in the gabbro include quartz, chlorite, clinozoisite, magnetite, sphene, apatite, and secondary biotite.

Late deformation has had a variable effect on the gabbro, from minor strain to spaced zones of high strain or shear. Minor strain appears as patchy or wavy extinction within platy amphiboles, and some local rotation of the plates. There has been crystallization of fine euhedra of similar amphibole in parallel trains both across earlier amphibole plates and, more abundantly, throughout feldspathic zones, along with micro-granulation of small areas of feldspar. In contrast, major strain appears 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. General granulation of plagioclase crystals has obscured their original bladed form, while indents to 'pyroxene' plates have closed and a sieve texture has been generated. Feldspathic and fine amphibole phases are wrapped around platy amphibole domains. There is local overprint of a sparse growth of ?cummingtonite which appears to be associated with tourmalinization.

The indications of strong rotation during later deformation is particularly prevalent in the Karramindie belt where rotation was probably caused by tightening and shearing of the refold against the major north–south shear marginal to the Depot Granodiorite (*Agd*).

The boundary between the gabbro sill and the country rock basalt is marked by a grey shale horizon (*Ash*) which is often several metres thick. The physical contrast between the enclosing basalt and these interflow sedimentary rocks provided the favourable path for the intruding magma.

Associated with these shales there are commonly one or more thin felsic schists which are derived from intrusive porphyry or volcaniclastic rock, and there is locally abundant quartz veining. The presence of these two features in the shale invariably indicates auriferous rocks. 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. The western margin becomes progressively dominated by subparallel sheeted veins and dykes of microgranite, pegmatite, and quartz over several hundred metres.

The gabbro is truncated by granitoid rock or covered by superficial deposits along the western margin of the Nepean belt, while on the eastern side the sill overlies a 2–3 m horizon of grey shales and felsic porphyries which define an open synclinal closure. The lower margin of the sill is slightly discordant with ocellar and pillowed high-Mg basalts (*Abm*) which form a thick screen on the southern side of the syncline. It is not clear at this locality whether a true succession is represented or whether the shale is the locus for thrusting of the gabbro over the basalt.

In the centre of the Saddle Hills belt a similar sill has a discordant outcrop pattern and an apparent thickness of 2 km. In the vicinity of Mount Herbert, it lies between komatiite and felsic volcaniclastic rock. This portion of the sill is fault bounded along strike and is foliated against the Celebration Dyke (Fig. 2). The northern limit of the sill is obscured by cover, while the western margin has intrusive, but generally foliated, contacts with basalt and tectonic contacts with ultramafic schists. Younging evidence within the sill, and occurrences of wallrock inclusions indicate that the sill overlies the felsic volcaniclastic rocks which occupy the core of an anticline; this is supported by younging evidence within nearby basalts and felsic volcaniclastic rocks. However, structural evidence indicates that this fold has been sliced and sheared so that many unit contacts are tectonic and the succession shuffled.

Mount Pleasant Sill

The Mount Pleasant Sill occurs in the vicinity of Mount Pleasant, on the northern boundary of KALGOORLIE, and is a 600 m thick, layered gabbro sill (*Aog*) which is exposed in a faulted anticlinal closure. It is concordant, overlain by grey shale and basalts, and is intruded at its base by granitoid rock and a large felsic porphyry body. Thin sheets of felsic porphyry have intruded the sill subconcordantly at all levels.

A detailed study of the petrology and mineralization of this unit has been made by Witt et al. (1991). The gabbro is best exposed on the eastern limb of the folded sequence. It appears to occupy the same stratigraphic position as the Three Mile Sill but has a better developed or preserved compositional layering.

Field evidence indicates that the sill developed through three stages of intrusion in which each injection of magma took place within the margins of the previous one but was asymmetrically disposed towards the upper portion. Each injection was differentiated internally and with similar asymmetry.

The margins of each injection are medium grained, mafic rich, and may grade into trachytic zones several metres thick. It is not clear if this igneous lamination is a flow-related texture or a result of static crystallization processes in the magma. Between these marginal zones, there is variable gradation from medium- to coarse-grained, melanocratic gabbro–dolerite with subophitic platy texture, to very coarse-grained, leucocratic 'anorthositic' gabbro with scattered short blades of pyroxene.

In thin section the gabbro shows gradational changes in composition and texture corresponding to the variations observed in the field. The pyroxene present is mainly augitic, although textural evidence suggests some orthopyroxene is present in some samples. It occupies more than 60% of the rock in darker layers and as little as 35% in lighter layers. Pyroxene textures range from weakly subophitic to ophitic, and pyroxene grains are finer than plagioclase in darker layers and coarser in lighter layers. Up to 2% interstitial quartz is present locally and skeletal opaques are scattered throughout.

The gabbro has been pervasively metamorphosed to greenschist facies, although some relict augite and labradorite cores are present in samples from the centre of the intrusion. Pyroxene is uralitized, plagioclase is saussuritized, opaques are altered to leucoxene, and carbonate and chlorite are abundant.

Powder Sill

The Powder Sill is a major gabbro–dolerite sill (*Aog*) which intrudes the felsic volcaniclastic pile on KALGOORLIE but is rarely seen on YILMIA. It reaches a maximum thickness of about 1000 m northeast of Kunanalling, but thins markedly southward. It is overlain by a leucocratic sill of granodiorite to tonalite composition (*Aol*) in the north.

The Powder Sill is mainly concordant, except northeast of Coolgardie where it forms a locally subconcordant, lit-par-lit injection complex. Within the sill, there is regional and local grain size variation from coarse to medium grained but there is sparse compositional layering apparent. The margins of the sill are poorly exposed but range from sharp to stoped to pillowed.

The sill is generally homogeneous with only a vague gradation from melanocratic margins to a slightly more mesocratic interior. In the sill, there are localized, faint wispy banding and occasional pegmatite patches which are similar in appearance to the overlying granodiorite. The grain size of the gabbro sill ranges from coarse to medium and there is an equigranular texture.

The contact between the gabbro sill and the underlying felsic volcaniclastic rocks is sharp. Northeast of Kunanalling there is a sharp boundary between gabbro and the overlying granodiorite–tonalite but to the south near Cattle Swamp the contact is gradational over a few metres. A contiguous marginal zone is marked by several metres of fine- to medium-grained, leucocratic rock which is homogeneous and contains evenly distributed, acicular amphibole crystals and local, pale spherulitic mottling. This horizon grades sharply into an very coarse-grained leucocratic rock of similar composition. In the leucocratic rock, very long (3 cm) blades and branching blades of amphibole are set in a matrix of plagioclase with minor quartz. There is an increase in quartz content (which remains minor) and a decrease in grain size up through the unit. The upper margin has only been seen northwest of Cattle Swamp where it has a sharp contact with felsic volcaniclastic rocks.

The Powder Sill has a composition of gabbro to hypersthene gabbro and is homogeneous, except for a slight upward increase in iron content and in the proportions of quartz and apatite. Pyroxene constitutes about 60% of the gabbro and occurs as stubby prismatic laths. Clinopyroxene is dominant, but there are textural relicts of some minor orthopyroxene. Plagioclase comprises 30–50% of the rock and occurs locally as tabular crystals with indications of cumulate texture. Where fresh crystals survive, they have a labradorite–bytownite composition. Minor phases present in the gabbro include primary or deuteric hornblende, interstitial quartz, Fe-Ti opaques, and apatite.

Greenschist facies metamorphism has variably recrystallized the primary assemblage of the gabbro but the igneous texture and mineralogy are generally discernible. Pyroxene is generally uralitized and is variably pseudomorphed by polycrystalline aggregates or single platy crystals of actinolite–hornblende. Plagioclase is variably saussuritized and recrystallization to oligoclase is common. Growth of chlorite and amphibole within plagioclase protocrysts imparts a darker colour to the rock. Opaques are altered to leucoxene, and veins of clinozoisite are scattered throughout.

The upper, leucocratic sill of granodiorite to tonalite (*Aol*) is composed of distinctive rock which is compositionally and texturally complex. There is an heterogeneous gradation within the quartz and feldspar from mainly irregular tracts of symplectic texture to mainly hypidiomorphic granular texture. Amphibole, which comprises 15–30% of the rock in the form of long and slender blades, is a blue-green variety of actinolite–hornblende similar to that in the lower mafic sill. It is not clear whether the amphibole pseudomorphs are after primary pyroxene or hornblende. Plagioclase occupies less than 35% of the rock and occurs as both equant euhedral plates and graphic intergrowths with quartz. Albitic compositions are considered to be metamorphic in nature. Quartz occurs as large crystals enclosing plagioclase and amphibole or as graphic intergrowths with feldspar which usually surround plagioclase euhedra. Epidote is a common accessory mineral.

The lower, mafic portion of the Powder Sill differs from other large sills lower in the succession in showing little apparent compositional or textural layering. It appears to have been intruded as a simple, single injection into the felsic volcaniclastic pile.

The method and timing of injection may be deduced from critical localities northeast of Coolgardie. In the vicinity of Two Dams, there was lit-par-lit injection of the gabbro–dolerite and numerous 5–10 m thick apophyses of the sill are separated by similar thicknesses of felsic countryrock. The margins grade into a gabbroic breccia with 0.5–2 cm, angular to subrounded fragments of felsic and mafic rocks.

Southeast of Red Lake, the sill has a pillowed margin against felsic volcaniclastic rocks. Pillows, up to 20 cm across, are composed of medium- to coarse-grained dolerite which is variably silicified (Fig. 20). Interpillow material is mainly dark hyaloclastite with coarse, matted amphibole blades, and occasional rinds and irregular patches of siliceous material. Silicification of the dolerite is more apparent towards the margins of the sill, and fragmented felsic volcaniclastic material is discernible between pillows.

The pillowed portion of this sill may be a result of immiscibility effects in heterogeneous magma but this does not explain the close association with the felsic rocks. They are more likely to have resulted from the intrusion of magma into wet sediments as described by Kokelaar (1982, 1986). It is inferred that the Powder Sill was emplaced penecontemporaneously with felsic volcanism and that the magma intruded partly consolidated volcaniclastic deposits. Where these deposits were still 'wet', the magma eroded them through volatile streaming before cooling as pillows against the hydrous host.

The relationship between the lower (mafic) and upper (leucocratic) sills northeast of Kunanalling is complex and equivocal. The upper sill is recognized only where the mafic sill is at its thickest, suggesting a genetic link. Graphic intergrowths of quartz and feldspar in the upper sill are typical of late-stage differentiates and some mineralogical textures are similar to those in the gabbro–dolerite. However, the lower sill is homogeneous and shows no broad-scale internal differentiation.

The contact between the sills is sharp and contains spherulitic mottling which is reminiscent of partial-melting textures (Emeleus and Forster, 1979). Sections of relict, hypidiomorphic granular texture which occur throughout the rock are inconsistent with a differentiate origin. The conflicting evidence suggests that the leucocratic sill is a hybrid which was derived, in part, from differentiation of a mafic magma and, in part, from a felsic or intermediate volcanic source. It is not clear whether mixing took place at depth or at the (current)

Figure 20. Pillowed mafic intrusive (*Aod*), Powder Sill, within felsic volcaniclastic rocks (*Afv*) near Red Lake.

level of intrusion. The occurrence of only minor amounts of intermediate composition rocks in regions which are otherwise rich in felsic and mafic rocks has been explained through turbulent magma mixing (e.g. Thompson, 1969). If this mechanism was the source of the nearby intermediate volcaniclastic rocks, then the leucocratic sill may be their subvolcanic equivalent.

Other mafic intrusions

Gabbro also forms small sills several metres thick within the basalt pile. They are scattered throughout the area, not usually correlatable, and probably of limited extent.

One thin sill is regionally persistent and is a good stratigraphic marker horizon as it intrudes the boundary between high-Mg basalt and komatiite which is marked by a grey shale. The sill is texturally distinct from 'doleritic' horizons which are common throughout the basalt pile; it has a markedly mottled appearance due to the development of single-crystal amphibole pseudomorphs of large (< 5 mm), equant, ophitic pyroxenes. The feldspar content is variable but locally abundant, and grains are coarse relative to pyroxene, giving the rock a weakly porphyritic appearance.

On the eastern margin of YILMIA near the Celebration Dyke (around AMG 568647) there is a large body (300 x 200 m) of layered gabbro. It is ovoid and elongate parallel to the enclosing porphyry body but embayed at its ends. On its western side the gabbro is coarse grained, very melanocratic and has a sharp boundary with the felsic porphyry, while on the eastern side it is medium to fine grained, locally very leucocratic, and has a sinuous boundary with the porphyry. Within the gabbro, compositional layering comprises bands of 'pyroxenite', streaky 'pyroxenitic' augen enclosed by plagioclase, and plagioclase; the layering lies at 30° to, and is cut by, the regional (north-northwest) foliation. Veins of fine-grained porphyry permeate the boundary between mafic and felsic layers in the gabbro.

In thin section, the gabbro shows evidence of metamorphism followed by metasomatism. Pyroxene has been replaced by blue-green actinolite in large (< 3 mm), poikiloblastic plates or acicular to fibrous laths. Andesine is recrystallized to elongate grains with amoeboid margins. Stoping by the enclosing porphyry has introduced polygonal lenses of quartz, biotite, and tourmaline with minor white mica, apatite, and recrystallized octahedral opaques. The metasomatic alteration that is apparent in the surrounding porphyry body is also present within the metagabbro; there is pervasive carbonate veining and alteration, retrogression of amphibole to chlorite, and nucleation of epidote and white mica.

The layered gabbro is interpreted as a xenolithic raft rather than an outlier of the Celebration Dyke. The parent body is unknown but it may be correlated with the gabbro–dolerite intrusion that occurs within the felsic volcaniclastic sequence (the Powder Sill). However, the presence of compositional banding is more characteristic of the lowermost Three Mile Sill. If this sill was emplaced and consolidated earlier, then wallrock fragments of it may have been caught-up in the rising felsic magma.

Where the metamorphosed dolerite unit (*Aod*), has been mapped in the Kalgoorlie–Boulder district, it corresponds to the Williamstown Dolerite, the Golden Mile Dolerite, and the Hannan Lake Gabbro of Keats (1987).

Archaean felsic intrusive rocks (*Afp*)

Intrusive felsic porphyry (*Afp*) occurs in small subconcordant bodies throughout the succession but are particularly common within the felsic volcaniclastic pile. Good examples of these intrusive rocks can be seen in the vicinity of Spargoville and along the eastern margin of the Saddle Hills.

Five kilometres northeast of Mount Herbert a large (8 x 2 km) felsic intrusive body intrudes medium to coarse tuff breccias on its western side, and fine tuffs and sedimentary rocks on its eastern side. Within 10 m of the contact, the country rocks become strongly foliated and there are 1–2 m apophyses of intrusive porphyry parallel to bedding. Near Ellen Dam, a dark cryptocrystalline porphyry with trachytic texture is considered to be a chilled marginal facies of this body.

Field relations indicate that the felsic body is probably composite with at least two phases of intrusion. There is a heterogeneous marginal zone, 100–200 m wide, which is rich in xenoliths, and a central zone containing two relatively homogeneous porphyry types which are distinguishable on the basis of relative abundance of phenocrysts and grain size of the matrix.

On its western side, the porphyry is purplish pink on fresh surfaces and contains abundant subhedral phenocrysts of feldspar and embayed quartz up to 5 mm in size. The very fine-grained matrix contains fine flakes of biotite and scattered, small, rounded biotite-rich xenoliths. On its eastern side, the porphyry has a grey cryptocrystalline matrix carrying fine, oriented biotite flakes; common subhedral phenocrysts of feldspar (< 1 cm); embayed quartz (< 1.5 cm); and scattered, subangular to rounded xenoliths of very fine-grained, biotite-rich rock.

The heterogeneous marginal zones comprise a strongly foliated porphyry matrix with 1–10 m wide bands containing common to abundant xenoliths of texturally distinct porphyry and tuff breccia. The matrix is compositionally similar to the porphyry on the eastern side but has a strong foliation defined by orientation of biotite, phenocrysts, and xenoliths. Biotite-rich xenoliths are streaked out to 10 x 5 cm lenses, while porphyry xenoliths are composed of the phenocryst-rich type found on the western side and form augen or, locally, schlieren. While only a mild internal foliation is present in these xenoliths, they have attenuated 'tails' which are strongly foliated and interfinger with the matrix. However, feldspar phenocrysts in the matrix have a random orientation. In the western zone there are also xenoliths of tuff breccia.

The porphyries have similar dacitic to rhyodacitic compositions and were probably batches of the same magma. Plagioclase phenocrysts of oligoclase composition and embayed quartz subhedra show some metamorphic recrystallization, with notable granulation around the 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 has been strong carbonate alteration with widespread sericitization of feldspar, and there are veinlets of carbonate and small amounts of pyrite.

These porphyries are similar in composition to the volcaniclastic rocks they intrude and are probably consanguineous. Therefore, they represent the exposed roots of a volcanic edifice mantled by its extrusive products.

The origin of the heterogeneous zones is unclear as they have some features akin to the adjacent tuff breccias and some magmatic features. They are interpreted to have been produced by a combination of both volcanic and magmatic processes. The western, phenocryst-rich, porphyry was intruded first at the top of a thick tuffaceous unit (*Aft*) and incorporates fragments of tuff breccia along its western margin. The eastern porphyry then intruded both sides of its precursor but mainly to the east. The marginal zone to the east represents a viscous stage of the later porphyry carrying stoped fragments of the earlier phase. The marginal zone to the west is similar but incorporates xenoliths of tuff breccia and earlier porphyry. A later deformation exaggerated the igneous layering.

Spargoville

Four kilometres southwest of Spargos Reward there is a problematic felsic lithology (*Af*) in two parallel outcrops which are disrupted by east–southeast trending faults. The symmetry of the outcrop distribution, combined with younging evidence in nearby volcaniclastic rocks, indicates that there is a minor fold which repeats the sequence. The rock is a hornblende-bearing, feldspar-phyric dacite with a primary foliation produced by mineral orientation and grain size variation. However, textural and mesoscopic details are equivocal as to whether this is a crystal tuff or a subvolcanic intrusive porphyry. Both such lithotypes are common to the east of this locality.

Mount Pleasant

Just north of Mount Pleasant, a felsic porphyry intrusion occupies the core of a faulted anticlinal closure and extends northward into BARDOC 1:100 000 sheet where it is more widely exposed (Witt et al., 1991). The porphyry intrudes the base of the Mount Pleasant Sill with a chilled margin up to 10 cm thick in places. Apophyses of the porphyry, up to several metres thick, occur within the sill where they are subconcordant to compositional layering.

The porphyry is homogeneous throughout, rhyodacitic in composition, with a white to pale green, cryptocrystalline matrix which carries abundant quartz and plagioclase and lesser K-feldspar phenocrysts. Phenocrysts are euhedral to subhedral and range from 1 to 6 cm in size. The groundmass is very fine-grained, hypidiomorphic granular, and comprised of quartz, feldspar, and minor biotite. Pervasive low-grade metamorphism has produced widespread sericitization.

Archaean granitoid rocks

Previous descriptions of the granitoid rocks of this region have been brief and superficial (e.g. Blatchford, 1899; McMath et al., 1953). Delineation of granitoid terranes on the first edition 1:250 000 maps of BOORABBIN (Sofoulis and Bock, 1963) and KALGOORLIE (Kriewaldt, 1968) was largely by photo-interpretation, and subdivision was limited to 'internal granites' (within greenstone belts) and 'external granites' (between greenstone belts).

More recently, attention has been given to the composition and genetic significance of these rocks. A brief summary of granitoid rocks in the Eastern Goldfields Province was presented by Williams (1974b). Bettenay (1977) studied a vast tract of the southeast Yilgarn Craton from LAKE JOHNSTON to LEONORA 1:250 000 sheets, producing the first major subdivision of the granitoid rocks. On the basis of structure and petrography, Bettenay (1977) adopted a 'kinematic' classification, relating granitoid type to the deformation history of the greenstone belts. Geochemical differences were found only between the 'external' granitoids and 'internal' granitoids. A detailed description of the granitoid rocks on BOORABBIN 1:250 000 sheet is given by Hunter (1989).

In this report, granitoid rock within the greenstone belts are described at Kanowna, Kintore, Bali, Calooli, Mungari, Karramindie, and Depot Hill, and four major types of granitoid rock are described between greenstone belts.

Banded gneiss (*An*)

Banded orthogneiss (*An*) occurs in an apparently discrete, arcuate body southeast of Nepean and also as xenoliths at the margins of Woolgangie and Burra Monzogranites. It is best exposed 1 km southwest of Connolly Siding on YILMIA and is not known on KALGOORLIE.

Precursors to this gneiss have been described on BOORABBIN 1:250 000 sheet as an intrusive complex of mesocratic gneiss, leucocratic gneiss, and pegmatite (Hunter, 1989). There are clear intrusive contacts between the older banded gneiss and the younger Burra and Woolgangie Monzogranites. However, there are no contacts exposed between banded gneiss and the adjacent greenstones so their relative ages remain unknown.

Figure 21A. Homogeneous banded gneiss (*An*), near Connolly Siding, derived from the deformation of streaky gneiss (*Anst*), intruded by dykes of more mafic granitoid rock.

Figure 21B. More heterogeneous banded gneiss (*An*), near Connolly Siding; it is similar to the gneiss shown in Figure 21A but less deformed, and intruded by narrow veins of pegmatite.

Isotopic ages of 2780 ± 60 Ma (Rb–Sr) and 2800 ± 150 Ma (Sm–Nd) were determined from banded gneiss samples from west of Connolly Siding (McCulloch et al., 1983).

Granitoid gneiss is characterized by persistent bimodal banding composed of biotite-rich and quartzo-feldspathic components (Fig. 21). The dark bands vary in thickness from one to several centimetres, rarely up to 10 cm, and generally lie in subparallel bundles. Leucocratic bands are comprised of quartz, feldspar, and a minor amount of biotite with a preferred elongation which presents a streaky augen fabric. The streaky gneissosity is generally subparallel to compositional banding but there are locations where discordance between the two indicates that the gneissosity was formed earlier.

Thin aplite, pegmatite, and quartz veins intruded the banded gneiss at various orientations prior to deformation. They have produced a finer, dispersed component of dark and light banding, or stringers with harmonic to disharmonic folding, depending on their original orientation. One or more phases of pegmatite (and some aplite) present in the banded gneiss are identified as post-dating the deformation that produced the banded gneiss and have intruded, at least in part, parallel to banding.

Overall, the banded gneiss has a granodiorite to monzogranite composition, although individual samples suggest some tonalitic affinities. Field and petrographic relations indicate that the major components of the gneiss were leucogneiss and mesocratic granitoid rock, which intrudes the latter. This association was deformed to produce the heterogeneous banded gneiss (*An*). The relative ages of the gneiss components is clearly seen west of Connolly Siding where the dark bands cut chevron folds in the streaky gneissosity of the pale bands.

If the banded gneiss is accepted as pre-greenstone continental crust, then the isotopic data of McCulloch et al. (1983) suggests that it was developed within 100 Ma of greenstone deposition. However, formation of the gneiss during greenstone deformation would still be within the limits of experimental error.

Streaky gneiss (*Anst*)

Streaky gneiss (*Anst*) is exposed in a 5 x 10 km belt located 15 km east of Burra Rock (Fig. 22). It is a medium- to coarse-grained, leucocratic granitoid with sparse biotite forming a weak to moderate foliation, which parallels a streaky orientation of feldspars and quartz. Quartz, which is relatively abundant, is often blebby and elongate parallel to biotite foliation, while locally it forms large, irregular grains enclosing feldspar. Local streaking in the gneiss defines random symmetrical folds.

In thin section, the rock is a biotite-bearing, oligoclase granodiorite containing sparse microcline and accessory apatite, zircon, and monazite. Its texture is allotriomorphic, granular, and weakly seriate.

Granitoid rock (*Ag*)

Unassigned granitoid rock (*Ag*) is mainly medium- to coarse-grained biotite monzogranite which is locally porphyritic. It occurs as small intrusions and as sheeted complexes with pegmatite and aplite within supracrustal belts. These granitoid bodies trend parallel to the host stratigraphy but may post-date deformation. Occasionally, dense swarms of granitoid sheets occupy up to 50% of outcrop.

Burra Monzogranite (*Agph*)

Burra Monzogranite (*Agph*) occurs in a northwest-trending zone in the southwest of YILMIA and is best exposed in the vicinity of Burra Rock. It is porphyritic and mainly homogeneous but has broad, heterogeneous marginal zones. It intrudes banded gneiss (*An*) and streaky gneiss (*Anst*) but is intruded by Woolgangie Monzogranite (*Agr*). There are no contacts exposed between Burra Monzogranite and nearby greenstones, and so their relative ages remains unknown.

Burra Monzogranite is an homogeneous granitoid which is characterized by abundant microcline phenocrysts up to 3 x 1 cm in size (Fig. 23). The phenocrysts are mainly subhedral and tabular to prismatic, and weathering picks out zonal distribution of inclusions and, occasionally, twinning.

The northeastern margin of this granitoid is a broad (< 1 km) zone of heterogeneity which increases in intensity outward. At the margins, the matrix is strongly foliated and is wrapped around feldspar megacrysts. There are abundant, penecontemporaneous granitoid dykes in this zone which were variably deformed with the Burra Monzogranite. Inclusions are rarely seen in the interior of the granitoid but are locally abundant within its marginal zone. They fall into three categories: narrow biotite-rich stringers representing entrained granitoid xenoliths and dykes; nebulous, irregular rafts of banded granitoid gneiss; and fragmental enclaves of amphibolitic xenoliths (Fig. 24).

Thin sections show the Burra Monzogranite to be a monzogranite with subhedral phenocrysts of microcline which have locally poikilitic margins. The coarse-grained granular matrix is mainly hypidiomorphic and comprises quartz, oligoclase, and biotite, with accessory zircon, apatite, magnetite, and some allanite and ilmenite. There are some coarse plagioclase crystals present, although they do not reach true phenocryst status. Quartz, which usually forms 25% of the matrix, sometimes occurs as large tracts enclosing plagioclase which formed by post-emplacement recrystallization.

In a regional context, the Burra Monzogranite is the most abundant granitoid between greenstone belts, comprising, with its variants, 55–60% of that terrain. There are variations in the size, shape, and abundance of the microcline phenocrysts as well as subtle variations in the texture of the groundmass. The heterogeneous marginal zones delineate oblate forms trending 150°

Figure 22. Streaky gneiss (*Anst*) near Connolly Siding.

Figure 23. Burra Monzogranite (*Agph*), west of Nepean: coarse biotite monzogranite containing abundant zoned euhedral megacrysts of microcline. It is intruded by a fine-grained, microphyric granitoid dyke.

which may represent individual plutons or a sheeted intrusions with open-style folding on a regional scale (Hunter, 1989). It is inferred here that this granitoid was emplaced magmatically and that the complex marginal zones were developed by a combination of stoping, dyke intrusion, and deformation caused by magma ballooning (see Ramsay, 1981).

The relative age of emplacement is deduced from intrusive relationships with adjacent granitoid bodies. At Durgulyie Rock, Burra Monzogranite intrudes banded gneiss with a stoped and lit-par-lit contact. The contact with streaky gneiss (*Anst*) is not exposed but an older age for the gneiss is inferred from relationships exposed west of Connolly Siding. Burra Monzogranite is intruded by dykes and small apophyses of Woolgangie Monzogranite (*Agr*) close to its margins.

A narrow, southeast-trending aeromagnetic anomaly, representing the attenuated remnants of the deformed Queen Victoria Rock greenstone belt, cuts the southwest corner of YILMIA (Hunter, 1988a). The greenstone belt is intruded by Burra Monzogranite in the vicinity of Queen Victoria Rock (central BOORABBIN 1:250 000 sheet) indicating a younger age for the granitoid. However, it is very similar to the Bali Monzogranite (*Agbl*) which was intruded early in the deformation history of the greenstones.

Isotopic age determinations have not been reported for the Burra Monzogranite on YILMIA. However, samples of a petrologically similar granitoid from Wheeler Rock (on LAKE JOHNSTON 1:250 000 sheet) gave a Pb–Pb age of 2632 ± 28 Ma (Oversby, 1975).

Woolgangie Monzogranite (*Agr*)

The Woolgangie Monzogranite (*Agr*) occurs on YILMIA in a 10 x 15 km ovoid body to the southeast of Nepean, where it is surrounded by banded gneiss. It also occurs as patches and apophyses near the margins of Burra Monzogranite, banded gneiss, and streaky gneiss.

It is a texturally distinctive, granular granitoid which is generally homogeneous and unfoliated, but has a xenolith-rich marginal zone. Intrusive relationships with other granitoids suggest that it is the youngest major granitoid on YILMIA. No isotopic age determinations have been published for this granitoid but unpublished data of petrologically similar rocks on BOORABBIN 1:250 000 sheet give Sm–Nd T_{CHUR} ages of 2840 ± 50 Ma (Boorabbin Rock) and 2 790 ± 30 Ma (Thursday Rock) (W. Libby, pers. comm., 1984).

Woolgangie Monzogranite is characterized by a coarse-grained granular appearance and a lack of any foliation (Fig. 25). Feldspar phenocrysts are either absent, or present as scarce, irregular, corroded remnants or subhedral to anhedral grains only slightly greater than groundmass in size. They have zones of inclusions which are emphasised by weathering. The margin of the granitoid body is defined by a narrow (< 1.5 km) zone of heterogeneity associated with abundant inclusions.

It has a composition of biotite monzogranite but is close to being granodiorite. The texture is allotriomorphic and seriate to equigranular, giving hand specimens a distinct granular appearance. Microcline is often perthitic and occurs as scattered small phenocrysts which always have poikiloblastic margins. Oligoclase is zoned and crystals tend to be more anhedral than subhedral. Complex resorption and replacement reactions are evident between plagioclase and both quartz and microcline. Quartz frequently shows strain and/or recrystallization to elongate domains of subgrains, while coarse, irregular patches enclose plagioclase islands and peninsulas. The biotite content is variable and accessories include apatite, zoned zircon, and allanite.

In general, Woolgangie Monzogranite is characterized by its distinctive granularity. This is manifest petrographically by its complex intergrain boundaries which are suggestive of recrystallization. There are also some vestiges of deformation, such as elongation of quartz and feldspar and the orientation of fragmentation of quartz domains. Although texturally distinct, this recrystallized granular granitoid is compositionally indistinguishable from Burra Monzogranite.

Four groups of xenoliths in the marginal zone to the Woolgangie Monzogranite are oriented in, and restricted to, zones trending northwest and occasionally north-northeast (Hunter, 1989). This suite of macroscopic inclusions is similar to that found in the Burra Monzogranite; however, there appears to have been a far more fluid relationship between host and inclusion, e.g. mafic xenoliths are commonly attenuated to zones of schlieren, and granitoid rafts are more thoroughly veined and assimilated, producing distinctly laminated zones of heterogeneity.

There is no evidence of deformation of the Woolgangie Monzogranite and it is always isotropic where it is free of inclusions or where it occurs as veins or dykes. All of the diagnostic dyke suites which are found in the Burra Monzogranite are cut by the Woolgangie Monzogranite.

Karramindie Monzogranite (*Agk*)

Karramindie Monzogranite (*Agk*) occurs in northeast YILMIA as a few small outcrops over a subcircular area of about 7 km^2. There are no outcrops revealing the nature of the contact but the body of the granitoid truncates the trend of the adjacent greenstone sequence.

There are no cross-cutting relationships with other granitoids to indicate relative ages but isotopic age determinations have given 2550 ± 25 Ma with Rb–Sr data (Turek, 1966) and 2705 ± 35 Ma with Pb–Pb data (Oversby, 1975) to the Karramindie Monzogranite.

The rock is notably leucocratic, fine to medium grained, and is homogeneous, except for sparse, ovoid biotite clots. There is no apparent foliation, although a weak, subhorizontal mineral alignment is seen in the northwest of the body, paralleling a major fault system. Pegmatite veins, a few millimetres wide, intrude a spaced network of fractures in the granitoid.

Figure 24. Xenolithic enclave in a heterogeneous marginal zone of Burra Monzogranite (*Agph*) near Bullabulling, 30 km west of Coolgardie. Angular blocks of metagabbro and metabasalt have been mechanically fragmented and attenuated.

Figure 25. Woolgangie Monzogranite (*Agr*), east of Nepean: coarse recrystallized biotite monzogranite with distinctive granular texture; prominant feldspars are corroded remnants of zoned megacrysts.

In thin section, the Karramindie Monzogranite has a biotite monzogranite composition and contains less than 6% red-brown biotite and minor secondary muscovite and chlorite. Oligoclase and K-feldspar are present in equal proportions as zoned laths which are commonly strained. Overall, the texture is granoblastic, seriate interlobate, but locally polygonal, suggesting that the granitoid has undergone middle to upper amphibolite facies metamorphism.

The metamorphic grade of the Karramindie Monzogranite is uncertain and raises problems of timing of emplacement. The discordant form and lack of foliation in the monzogranite suggest that the intrusion post-dated maximum deformation, hence maximum metamorphism, of the adjacent greenstones. Bettenay (1977) included the K-rich Karramindie Monzogranite in his suite of late-intruded 'fractionated leuco-adamellites' which have distinctive trace-element patterns.

The Karramindie granitoid has been the subject of a number of isotopic age determinations which are presented in Table 2. Chemical similarities between the Karramindie and Mungari Monzogranites led Oversby (1975) to speculate that they may be 'separated outcrops of a single intrusion continuous at depth'. However, the lead isotope systematics indicate significantly different ages of intrusion with the Mungari pluton being the younger.

Depot Granodiorite (*Agd*)

Depot Granodiorite (*Agd*) occurs in northeast YILMIA where it forms a 10 x 20 km ovoid body elongated parallel to the trend of the adjacent greenstones. It is best exposed at Depot Hill and Horse Rocks, and there are intermittent exposure of its contacts to the east and west of those outcrops.

The granitoid is heterogeneous where it carries nebulous xenoliths and is cut by abundant granitoid and pegmatite dykes. There is a broad (< 500 m) zone of strong foliation along its eastern and western margins. Cross-cutting relationships with other granitoids are not known but it has are good intrusive contacts with the enclosing greenstones.

Depot Granodiorite is medium to coarse grained with a streaky, granular matrix carrying scattered, rounded ?phenocrysts of feldspar. A strong foliation with low to moderate dip is apparent around the margins for several hundred metres but no lineation was observed.

Compositionally, it is a hornblende-bearing leuco-granodiorite to leuco-tonalite with a polygonal to interlobate, granoblastic texture. Hornblende comprises up to 10% of the rock with a generally porphyroblastic habit and is locally associated with green clinopyroxene. Plagioclase is dominantly oligoclase but with thin albitic rims and patches, apparently partial melt products. A mild gneissose fabric is also exhibited by quartz. Minor amounts of epidote, apatite, and allanite are present.

The northern margin of the Depot Granodiorite terminates abruptly against the Celebration Dyke and a fault parallel to Change Creek (at AMG 440620), whereas its southern margin appears to form a poorly exposed feather-edge contact with the greenstones in the Spargoville area. A distinct stoped margin with metasedimentary rocks is found on its western side; the presence of relict garnet and cordierite indicates a narrow contact aureole. There has been some deformation parallel to a major shear which clips the boundary between sedimentary rocks and other greenstones to the west. A similar intrusive margin is inferred for its eastern side but this has been obscured by a major shear which follows the boundary between the Depot Granodiorite and metasedimentary rocks. Near the northeastern margin a series of minor dextral shears up to 30 cm wide trend towards the northeast. Resolution of their geometry relates these shears as en-echelon sets to the major marginal shears.

The textural features of this granitoid, together with the hornblende–clinopyroxene mineralogy, indicate that it has experienced middle to upper amphibolite facies metamorphism. Archibald and Bettenay (1977) favoured a solid-state diapir mechanism for its emplacement and associated the dynamic metamorphism with this event. There are, however, clear indications of magmatic margins which have been subsequently modified by shearing (Hunter, 1989). The latest related intrusions were barren pegmatite dykes up to 2 m wide which post-date foliation.

Calooli Monzogranite (*Agc*)

The Calooli Monzogranite (*Agc*) forms a homogeneous, 10 x 15 km ovoid body just west of Coolgardie. Small, isolated outcrops occur along the margins of the southern half of the granitoid but the interior and northern half are poorly exposed. It has deformed magmatic contacts with the greenstones of the Coolgardie and Comet Hill areas which separate it from adjacent granitoid bodies. The age of emplacement is uncertain as there are neither published isotopic data nor any known cross-cutting relationships with other granitoids.

The Calooli Monzogranite is a medium- to coarse-grained, homogeneous, non-foliated granitoid rock with an equigranular texture. It is regarded as aphyric, although scarce corroded remnants of feldspar crystals occur and quartz grains appear prominent. In a narrow (< 50 m) marginal zone the monzogranite is variably foliated and locally protomylonitic.

In thin section, the monzogranite shows weak recrystallization and deformation features (e.g. strained quartz) but retains a well developed hypidiomorphic texture. Plagioclase and K-feldspar are present in approximately equal amounts, while accessory minerals include biotite, muscovite, magnetite, and garnet. The garnet is anhedral to subhedral, up to 1 mm in size, and colourless but variably 'dusted' with inclusions. In its foliated margin, the Calooli Monzogranite is highly recrystallized to a fine-grained, inequigranular rock. Scattered anhedral to irregular relict grains of quartz and feldspar are set in a fine-grained, microgranoblastic base of quartz, plagioclase, and K-feldspar. A foliation is

Table 2. Radiometric age determinations, Eastern Goldfields

Age	*Method*	*Locality*	
PROTEROZOIC DYKES			
2043 ± 40 Ma	K–Ar	*Queen Victoria Rock*	(a)
2085 ± 17 Ma	Rb–Sr	*Kambalda*	(b)
2420 ± 30 Ma	Rb–Sr	*Celebration and Jimberlana Dykes*	(c)
2411 ± 55 Ma	Sm–Nd	*Jimberlana Dyke*	(n)
FELSIC VOLCANICS			
2595 ± 40 Ma	Rb–Sr	Kalgoorlie	(d)
2780 ± 30 Ma	Sm–Nd	*Kanowna*	(e)
MAFIC AND ULTRAMAFIC VOLCANICS			
2675 ± 35 Ma	Rb–Sr	Kalgoorlie	(d)
2720 ± 10 Ma	Pb–Pb	*Kambalda*	(f)
2730 ± 30 Ma	Pb–Pb	*Kambalda*	(g)
2760 ± 30 Ma	Sm–Nd	*Ora Banda*	(g)
2790 ± 30 Ma	Sm–Nd	*Kambalda*	(h)
3262 ± 44 Ma	Sm–Nd	*Kambalda*	(i)
GRANITOIDS			
(Within greenstone belts — synkinematic)			
2550 ± 25 Ma	Rb–Sr	Karramindie	(c)
2705 ± 35 Ma	Pb–Pb	Karramindie	(j)
2585 ± 35 Ma	Rb–Sr	Mungari	(c)
2640 ± 35 Ma	Pb–Pb	Mungari	(j)
2760 ± 70 Ma	Pb–Pb	*Kambalda*	(j)
2820 ± 15 Ma	U–Pb	*Kambalda*	(m)
(Between greenstone belts — postkinematic)			
2600–2690 Ma	Rb–Sr	Coolgardie	(d)
2632 ± 28 Ma	Pb–Pb	*Lake Johnstone (Agph)*	(j)
2840 ± 50 Ma	Sm–Nd	*Boorabbin Rock*	(o)
2790 ± 30 Ma	Sm–Nd	*North of Diamond Rock*	(o)
GNEISS			
2570 ± 27 Ma	Rb–Sr	Stennet Rocks	(c)
2600–2690 Ma	Rb–Sr	Coolgardie	(d)
2671 ± 79 Ma	Pb–Pb	*Norseman*	(j)
2700 ± 97 Ma	Pb–Pb	*Yilgarn*	(k)
2780 ± 60 Ma	Rb–Sr	Connolly Siding (*An*)	(l)
2800 ± 100 Ma	Sm–Nd	Connolly Siding (*An*)	(l)

NOTE: Localities shown in italics are on adjacent map sheets

(a) CSIRO, 1976
(b) Roddick, 1974
(c) Turek, 1966
(d) Turek and Compston, 1971
(e) Fletcher et al., 1984
(f) Roddick, 1984
(g) Chauval et al., 1985
(h) McCulloch and Compston, 1981
(i) Claoué-Long et al., 1984
(j) Oversby, 1975
(k) Bickle et al., 1983
(l) McCulloch et al., 1983
(m) Compston and Pidgeon, unpubl.
(n) Fletcher et al., 1984
(o) Fletcher, unpubl.

manifest in the oriented growth of secondary white mica (5%) and the entrainment of relict coarser grains in the monzogranite.

The main body of the Calooli Monzogranite is homogeneous, biotite bearing, with very scarce xenoliths and aplite dykes. At a site 3 km southwest of Coolgardie, a borehole was sunk 915 m into the granitoid in a vain search for artesian water (Blatchford, 1899). Samples of the core, described briefly by Blatchford (1899), contain 'evenly distributed' hornblende rather than biotite. Bettenay (1977) assigned this pluton to his 'fractionated leuco-adamellites' group which represents late-stage liquids extracted from major post-kinematic granitoids.

The general form of the granitoid margin is smooth and continuous with no major apophyses or embayments. The contact is broadly subparallel to the enclosing greenstone trends but there is some acute cross-cutting.

In a zone 20–50 m wide, the margin of the granitoid shows an outward gradation from an isotropic texture, through weak biotite orientation, to strong general foliation. There is a 10–20 m transition zone where narrow bands (< 50 cm) of protomylonitic granitoid rock are interleaved with mafic and ultramafic schists derived from the greenstones. Similar styles of contact which have been described elsewhere in this region between granitoid gneiss and greenstones have been attributed to tectonic interleaving during a subhorizontal thrust event which preceded regional folding (e.g. Platt et al., 1978; Spray, 1985).

The Calooli Monzogranite cuts across the S_1 foliation which is attributed to a low-angle thrust event, and was, therefore, intruded later. There is also an apparent gradation from homogeneous granitoid rock to foliated, interleaved margin rocks. These features suggest that the marginal interleaving was due to magmatic, lit-par-lit intrusion (post-S_1) and that the foliation was imparted later. The foliated interleaved margin represents a zone of ductility contrast which became the locus of stress release during regional deformation.

Bali Monzogranite (*Agbl*)

The Bali Monzogranite (*Agbl*) is exposed in 10 x 45 km arcuate zone located 13 km west of Coolgardie. The body is bounded by the Kunanalling Shear Zone and by greenstones of the Mount Burges–Comet Hill belt to the east and of the Gibraltar–Jaurdi belt to the west. Isolated outcrops of granitoid rock are common along its margin and scattered within the interior of the unit.

The monzogranite is essentially homogeneous but with deformed magmatic contacts against surrounding greenstone belts. The age of emplacement is uncertain as there are neither published isotopic data nor any known cross-cutting relationships with other granitoids.

The Bali Monzogranite is a coarse-grained, homogeneous, porphyritic rock. Tabular microcline phenocrysts, 1–3 cm in length, are abundant and commonly show concentric erosional patterns on weathered surfaces. The inequigranular matrix contains large (0.5–0.7 cm), rounded, quartz crystals or clusters. In a narrow (< 100 m) marginal zone, the monzogranite is variably foliated and locally protomylonitic with a distinct augen texture.

In thin section, the microcline megacrysts are subhedral to euhedral in form and contain plagioclase inclusions confined to concentric zones. The megacrysts are set in a hypidiomorphic granular base of calcic plagioclase, quartz, and K-feldspar, with minor amounts of biotite (2–3%), and accessory opaques, apatite, and zircon. Plagioclase shows oscillatory zoning and is weakly saussuritized. Myrmekite is scattered throughout the rock.

The foliated margin of the Bali Monzogranite preserves gradational recrystallization to fine-grained, inequigranular, mildly augen-textured rock. A weak foliation was first developed through poorly defined zones of recrystallization that affected mainly K-feldspar and quartz. Biotite grains show a vague reorientation in these zones and there is some subparallel growth of new muscovite. In more foliated portions of the margin there is a moderately developed porphyroblastic texture; some quartz has recrystallized into elongate grains and there is up to 1% muscovite in subparallel trains. Strongly foliated rocks of the granitoid margin are about 60% recrystallized and composed of a fine- to medium-grained, granoblastic groundmass surrounding coarser relict crystals of microcline, quartz, and plagioclase which are generally equant and show minor flattening and attenuation. Subparallel orientation of biotite with minor muscovite defines the foliation.

From Grosmont to Mount Burges, the Bali Monzogranite lies on an arcuate trend parallel to the western margin of the Calooli Monzogranite. It is mainly homogeneous and isotropic with margins that are strongly foliated and veined by pegmatite and aplite. However, outcrops between West Canegrass Dam and Eight Mile Rock Dam have a weak to moderate foliation indicating that a concealed greenstone margin may exist just to the west. Detailed aeromagnetic data reveals a concealed continuity between the greenstones at Jaurdi Hill to the northwest and those to the southwest at Coondarrie (Aerodata, 1983). There is also a strong aeromagnetic lineament which coincides with a photo lineament trending northeast through West Canegrass Dam. Thus, the lithologically equivalent granitoid which extends from West Canegrass Dam to Kunanalling is considered to be a block of Bali Monzogranite which has had an apparent dextral offset of several kilometres. Eight kilometres north of Bali, the granitoid is cut by a set of narrow shears with sinistral offset at 105°.

The general form of the granitoid margin is smooth and continuous with no major apophyses or embayments. The contact is broadly subparallel to the enclosing greenstone trends but some acute cross-cutting is apparent. In a zone 50–100 m wide, the margin of the granitoid shows an outward gradation from an isotropic texture, through weak biotite orientation, to strong general foliation with a relict augen texture. Within this zone, quartz veinlets and spaced shears parallel to the contact become wider and more abundant. A strong upright lineation is developed in the plane of the foliation.

There is a 10–20 m transition zone in which narrow bands (< 50 cm) of protomylonitic granitoid rock are interleaved with lineated mafic and ultramafic schists derived from the greenstones. The greenstone schists grade outward to rocks with relict thermal metamorphism before regionally metamorphosed varieties are apparent. Abundant narrow dykes of aplite, pegmatite, and quartz intrude this transition zone parallel to its trend.

Bettenay (1977) assigned this pluton to his 'synkinematic' group, describing it as a biotite–muscovite leucogranodiorite with a highly recrystallized interior. The marginal zones were described as garnet–muscovite aplogneiss.

Mungari Monzogranite (*Agmu*)

The Mungari Monzogranite (*Agmu*) forms a well exposed, 4 x 8 km ovoid body 12 km northeast of Coolgardie. It is homogeneous and isotropic, except for a moderate foliation within a few metres of its western margin. It has a sharp magmatic contact with enclosing felsic volcaniclastic rock and a broad thermal metamorphic aureole to the south.

The age of emplacement has been determined as 2620 ± 20 Ma by Rb–Sr data (Compston and Turek, 1973) and 2640 ± 35 Ma by Pb–Pb data (Oversby, 1975).

The Mungari Monzogranite is a medium-grained, equigranular rock with a slightly granular appearance and contains scattered, subhedral to anhedral, zoned feldspars which appear slightly coarser than the groundmass. The rock is isotropic, except within 5 m of the western contact where a moderate to strong foliation is developed parallel to the greenstone trend.

In thin section the granitoid is a medium, even-grained rock with relict allotriomorphic to hypidiomorphic granular texture. It comprises quartz, zoned K-feldspar, oligoclase, and minor red-brown biotite, and accessory zircon, opaques, and fluorite. Mild alteration has produced turbid feldspars, variable chloritization of biotite, and the growth of secondary muscovite. Quartz and some plagioclase show strained extinction and incipient recrystallization into domains. There are scattered occurrences of myrmekitic intergrowths and annealed microshears.

The exposure of Mungari Monzogranite lies within a smooth ovoid perimeter which may not represent its true lateral extent. The northern margin is concealed and there are no surface or subsurface indications (e.g. by aeromagnetic data or drilling) of its actual location. The southern margin appears well constrained by delimiting outcrops and exposed contacts but a high-grade thermal aureole extends as far south as Brown Lake, 3.5 km east-southeast of Mount Robinson. The Mungari Monzogranite is bounded to the west by a < 300 m wide zone of andalusite schist (*Afsa*) which was developed through shearing of a pelitic hornfels. These features suggest that a southerly extension of the Mungari Monzogranite underlies the felsic volcaniclastic rock at shallow depths.

Chemical compositions of this granitoid reported by Glikson and Sheraton (1972) and Oversby (1975) reveal greater K–Na ratios than typical monzogranites of the region, and Bettenay (1977) reported distinctive trace element patterns.

Kintore Tonalite (*Agkn*)

The Kintore Tonalite (*Agkn*) occurs in northwest KALGOORLIE, in the vicinity of Kintore, where it forms a 2 x 5 km ovoid body. It is poorly exposed and outcrops are confined to its southern and northern margins. No cross-cutting relationships with other granitoids are apparent but it has intrusive contacts with the enclosing greenstones.

The tonalite is medium grained and equigranular with distinctive, prismatic feldspars. It is homogeneous in the vicinity of Kintore and the Last Chance mine but develops a very strong foliation southeast from the Last Chance mine and southwest from the Ridge mine.

In thin section, it has a well developed hypidiomorphic granular texture and contains abundant, square to rectangular, plagioclase crystals. Plagioclase shows strong oscillatory zoning with calcic cores and albitic rims; moderate to strong sericitic alteration mimics the zoning. Quartz is typically anhedral and is interstitial to plagioclase. Reddish-brown biotite constitutes 2–3% of the rock, whereas K-feldspar is rare or absent.

Nine Mile Monzogranite (*Agnm*)

The Nine Mile Monzogranite (*Agnm*) occurs in the northeast corner of KALGOORLIE where it represents the southern extension of a large (12 x 30 km) body on BARDOC 1:100 000 sheet (Witt, 1990). It is best exposed in the vicinity of Kanowna Homestead but outcrop is generally poor and dominated by rubble and lateritized breakaways. The rock is characterized by abundant, large subhedral to euhedral, microcline phenocrysts set in a mildly granular quartzo-feldspathic matrix. It is petrographically similar to the Bali and Burra Monzogranites. A detailed description of the Nine Mile Monzogranite will appear in Witt (1990).

Pegmatite (*Agp*)

Pegmatite (*Agp*) is ubiquitous throughout KALGOORLIE and YILMIA with an extensive history of intrusion. It is coarse to very coarse grained and range from deformed veins in orthogneiss to undeformed bodies in greenstone belts and granitoids. The main constituents are quartz, microcline, and albite with variable amounts of biotite. Larger bodies tend to be compositionally zoned parallel to their walls, and graphic intergrowths of quartz and feldspar are common.

Pegmatites within the granitoids are barren of economic minerals and usually deficient in biotite. However, where they occur within greenstones, there is usually a suite of exotic minerals present, of which economic or subeconomic concentrations are common. Minerals which have been commercially extracted from these pegmatites include feldspar, biotite, tantalite, beryl, and lithium-bearing feldspar, pyroxene, and mica. Black to dark green tourmaline and red-brown garnet are common constituents of pegmatites in greenstone. Details of the major pegmatites and their mineralogy are given in the economic section of the explanatory notes for BOORABBIN 1:250 000 sheet (Hunter, 1989).

Thermal aureoles to these pegmatites are variably developed and may be absent, narrow (< 1 m at Mount Marion), or broad (12 m at Londonderry). The aureoles may contain biotite and tourmaline as a result of hydrothermal alteration; at Mount Marion, there is an exotic amphibole (holmquistite) which is a product of hydrothermal alteration (Wilkins et al., 1970).

The provenance of the pegmatites is unclear as the bodies are relatively small and isolated. In describing the Mount Marion pegmatite, Ross (1964) cited the nearby Depot Granodiorite as a probable source; a correlation which is consistent with a similar deposit at Ravensthorpe (Ross, 1964) and with the observations of Rowe (1954) on the occurrences of Li-pegmatites in Canada. However, since the YILMIA pegmatites are undeformed and strongly discordant to lithological and structural trends, they must have been emplaced later than the Depot Granodiorite. Field relations suggest that the larger pegmatites are likely to be related to the later fractionated granitoids, such as the Karramindie Monzogranite. A petrogenetic grid for Li-rich pegmatites erected by London (1984) establishes that 'under the quartz-saturated conditions that prevail in pegmatites, stability relations among the Li-aluminosilicates are a function of P and T and are largely independent of the nature and proportions of other phases'. Using this grid in a qualitative sense, it can be deduced that the pegmatites at Londonderry were emplaced at a lower crustal level (2 kb) than those at Mount Marion, possibly by an approximately factor of two.

Stratigraphy

The greenstones of KALGOORLIE and YILMIA lie towards the western margin of the broad Norseman–Wiluna granite–greenstone terrane. There is a limited group of lithotypes within the terrane but the individual units are discontinuous and 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, either along or across strike, is difficult (Tables 3 and 4). Even within local successions, critical boundaries may be concealed or tectonized.

Previously published successions

A synthesis of early geological work at Kalgoorlie by Forman (1937a) established a gross stratigraphic order which has changed little since, except for the relative timing of granitoid emplacement. He considered that a group of 'Older Greenstones' at Kalgoorlie were succeeded by a series of clastic rocks which were intruded by basic rocks ('Younger Greenstones'), granite, and porphyry. Forman regarded the 'Kurrawang Beds' having been deposited unconformably during the Proterozoic and the whole succession was cut by late Proterozoic or Cambrian basic dykes.

McMath et al. (1953) integrated reconnaissance mapping of the Coolgardie area with detailed examinations of selected mine groups. Their studies led to the first synthesis of the structure and stratigraphy of the area, while their maps defined the trends of a major mafic–ultramafic sequence. He proposed a thick, complex succession (Fig. 26) comprising four horizons of ultramafic rock alternating with four mafic basalt horizons, with the upper two basalts separated by a major gabbro sill. This succession was correlated with the 'Older Greenstones' at Kalgoorlie. To explain the current disposition of lithologies, it was proposed that the sequence underwent regional doming followed by intense cross-folding, before being intruded by granitoids. The clastic rocks to the east of Coolgardie (the 'Whitestone Series') were interpreted as younger and deposited on a disconformity.

In the first edition of BOORABBIN 1:250 000 sheet, Sofoulis and Bock (1963) maintained the overall configuration of lithologies from the previous work but delineated further divisions of both mafic and ultramafic units.

Woodall's (1965) Kalgoorlie stratigraphy preserved Forman's (1937a) two lowermost divisions but introduced a detailed subdivision of the greenstones. At the base of the succession was an ultramafic unit which was overlain by basalts containing interflow sedimentary rocks and two mafic sills. The greenstones were overlain by felsic to intermediate volcaniclastic and volcanic rocks.

Glikson (1971a,b, 1972) has presented a detailed study of the clastic rocks between Coolgardie and Kalgoorlie, dealing with geochemistry, stratigraphy, petrology, and structure. He interpreted the succession as continuous from the 'ophiolites' of Coolgardie to the conglomerates at White Lake, comparing it to geosynclinal sedimentation adjacent to an emergent volcanic terrain. Glikson envisaged the trend of basin evolution was from a pelitic facies into a greywacke–slate association and subsequently into a greywacke–conglomerate association; sediment deposition was punctuated by volcanic activity ('ophiolites') and at least one unconformity. Rocks of his 'Kalgoorlie System' were considered to overlie this succession.

Williams (1969, 1970) erected the first regional stratigraphic succession northeast of this area, based on a theory of volcanic cyclicity. He maintained the association of a mafic–ultramafic lower group with a felsic volcano-sedimentary upper group. However, the regional distribution of similar lithotypes was explained by repetition of the associations in a series of three mafic to felsic volcanic cycles.

Exploration mapping during the nickel boom delineated the main ultramafic units but less effort was made to subdivide or rationalize the remaining lithologies. A regional synthesis of the data generated during that period was presented by Gemuts and Theron (1975). Their sequential stratigraphy (Table 3) continued the emphasis on complex layer-cake stratigraphy affected by relatively simple structural modification. On the basis of lithological association, the Coolgardie succession was assigned to sequences 3 and 4, equating it with the nickel and gold bearing areas of Kalgoorlie and Norseman. The remaining greenstones were assigned to the higher level, sequences 5 to 8, similar to the Yilmia Hill and Higginsville areas. Such a division requires a major structural and stratigraphic break to the southeast of Coolgardie, for which there is little evidence.

Table 3. Published regional stratigraphic successions

Gemuts and Theron (1975) *Coolgardie–Norseman*	*Williams (1969, 1970)* *Kurnalpi*	*Gresham and Loftus-Hills (1981)* *Kambalda–Peninsula*	*Woodall (1965)* *Kalgoorlie*	
Sequence 8 Polymictic conglomerate and pebbly greywacke	*Association V* Pebbly greywacke			CYCLE 3
Sequence 7 Acid tuffaceous rocks and acid volcanic breccia; some acid extrusive rocks		Mafic and felsic volcanics, greywackes, mafic intrusives		
Sequence 6 High-Mg basalt, ultramafic rocks; minor chert, black slate, and tholeiitic basalt	KALPINI FORMATION Basic to intermediate extrusive and intrusive rocks, ultramafic intrusive rocks; minor clastic rocks and chert	BLUEBUSH SEQUENCE Bluebush hanging-wall basalt Bluebush ultramafic rocks Bluebush footwall basalt		
Sequence 5 Conglomerate, arkosic greywacke, and argillite; minor tholeiitic basalt; basal conglomerate	*Association IV* GUNDOCKERTA FORMATION Turbidite sequence; clastic sequence, conglomerate and sandstone			CYCLE 2
Sequence 4 Top of sequence gradational to sequence 5; greywacke, minor chert and black slate; acid extrusive rocks and feldspar porphyry intrusives; minor high-Mg basalt	Acid volcanic complexes	Felsic volcanics, greywackes, argillites	BLACK FLAG BEDS Tuff, agglomerate, acid to intermediate lavas, slate, shale, greywacke, quartzite	
Sequence 3 Black chert marker; tholeiitic basalt, and four horizons of ultramafic rocks; intercalated slate and chert bands; minor high-Mg basalt	*Association III* MULGABBIE FORMATION Basic intrusive and extrusive rocks; ultramafic rocks, intermediate, and acid extrusive rocks; minor cherts	KAMBALDA SEQUENCE Kambalda hanging-wall basalt upper member 'Sediment–intrusive complex' Kambalda hanging-wall basalt lower member Kambalda ultramafic rocks	Golden Mile Dolerite Paringa Basalt Williamstown Dolerite Kapai Slate Devon Consols Basalt Hannans Lake Serpentinite	
Sequence 2 Banded iron-formation, greywacke, shale, conglomerate, and sandstone	*Association II* GINDALBIE FORMATION Clastic sequence			CYCLE 1
Sequence 1 Greywacke and acid lithic tuff; tholeiitic basalt	*Association I* MORELANDS FORMATION Tholeiitic and ultramafic lavas	Kambalda footwall basalt		

Table 4. Published stratigraphic successions of the Kalgoorlie and Coolgardie areas

Forman (1937a) *Kalgoorlie*	*McMath et al. (1953)* *Coolgardie*	*Woodall (1965)* *Kalgoorlie*	*Glikson (1971b)* *Coolgardie*
Dolerite and gabbro			
..........*igneous contact*..........			
KURRAWANG SERIES			KURRAWANG BEDS Polymictic metaconglomerate, pebbly metagreywacke
			..........*unconformity*..........
Granite and porphyry	Granite (gold and economic pegmatite mineralization) Gneisses (period of granitization)		MUNGARI BEDS (upper) Black Flag metasediments: metagreywacke, metasiltstone, slates
Younger Greenstones	'Meta Gabbros and Dolerites (Younger Greenstones)'		RED LAKE OPHIOLITES Mafic–ultramafic volcanics
			..........*unconformity*..........
KUNDANA SERIES			
..........*unconformity*..........			
WHITE FLAG– YINDARLGOODA SERIES		BLACK FLAG BEDS Tuffs, agglomerates, acid to intermediate lavas, slates, shale, greywackes, quartzite	MUNGARI BEDS (middle) Brown Lake metasediments: phyllite, greywacke, metasiltstone, argillite
..........*unconformity*..........			MT ROBINSON OPHIOLITES Mafic–ultramafic volcanics
BLACK FLAG SERIES Tuffaceous	EASTERN and WESTERN META SEDIMENTARY SERIES (= Whitestones Series)		MUNGARI BEDS (lower) Gunga meta-argillites: siliceous meta-argillites, slates
	..........*unconformity*..........		
KALGOORLIE SERIES (= Older Greenstones)	COOLGARDIE SERIES (= Older Greenstones)	GOLDEN MILE DOLERITE Layered basic sill	COOLGARDIE OPHIOLITES Mafic–ultramafic volcanics
	Bonnie Vale belt Hampton belt Tindals belt Lord Bobs belt	PARINGA BASALT Basalt metalavas, minor intercalated shales	Bonnie Vale belt Hampton belt Tindals belt Lord Bobs belt
		WILLIAMSTOWN DOLERITE Layered mafic–ultramafic sill	
		KAPAL SLATE Graphitic slate	
		DEVON CONSOLS BASALT Basalt metalavas	
		HANNANS LAKE SERPENTINITE Massive fine-grained serpentinite	

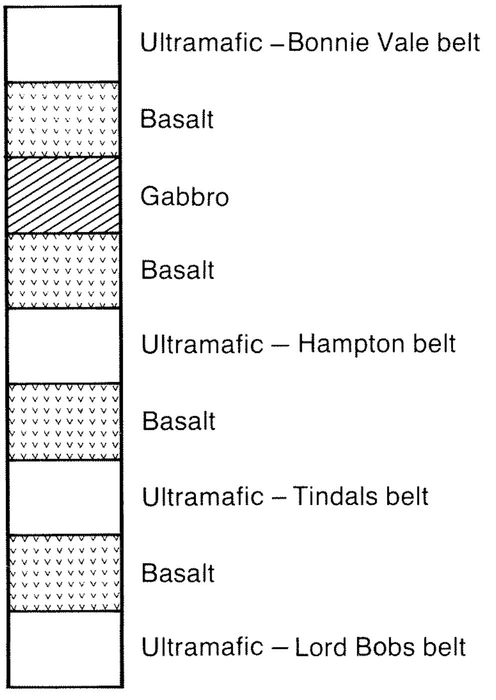


Figure 26. Coolgardie succession according to McMath et al. (1953).

Proposed stratigraphy

A combination of regional (Hunter, 1989) and detailed studies (this report) of the same area has led to the proposal of a local stratigraphic succession. The stratigraphy detailed below is relatively simple and accommodates the minor lateral variations to be expected across such an expanse of dominantly volcanic terrain. The observed complex distribution of lithologies of this succession is the result of multiple events of folding and faulting, punctuated by stages of granitoid intrusion. The succession can be best observed in the Coolgardie area where exposure is reasonable, refolding is moderately open, and tectonic attenuation is relatively minor. To the southeast, there is progressively tighter refolding with pervasive slicing and shearing which combine to produce complex occlusions and repetitions of portions of the succession.

The stratigraphic interpretation presented here (Fig. 27) evolved from a number of critical observations which are exemplified in the Coolgardie area but are applicable to some degree throughout the area.

There is a marked incidence of symmetry within most greenstone belts which suggests that the multiplicity of similar lithological units is mainly due to structural repetition rather than cyclical facies recurrences. This is supported by the complementary orientations of asymmetrically disposed marker horizons within units.

Several discrete marker horizons have been recognized at a number of levels in the succession. Detailed mapping of these laterally extensive 'markers' has enabled delineation of multiple phases of open to tight folding.

Younging indicators, such as lava pillows, flow-top breccias, compositional layering, textural grading and sedimentary structures, are ubiquitous but variably preserved. When taken in combination they complement the tectonostratigraphic interpretation by indicating relative ages of contiguous horizons.

Structural fabrics, e.g. folded layer-parallel foliation, crenulation cleavage and vertical lineation, indicate a complex tectonic history involving several stages of deformation. These observations are not compatible with a simple open-fold history.

The succession

Stratigraphic nomenclature used in this section follows the guidelines laid down by Staines (1985). The proposed stratigraphic succession consists of a single association of two distinct lithological groups. The lower group, the Coolgardie Group, contains mafic to ultramafic flows and minor clastic rocks which are intruded by several major gabbro sills. The upper group, the Black Flag Group, contains felsic to intermediate volcaniclastic rocks with minor flows and intrusions. One gabbro–dolerite sill intrudes the lower portion of the upper group. The Black Flag Group is overlain by a terrigenous conglomerate and sandstone unit, the Kurrawang Formation. Both groups were deformed and metamorphosed before being intruded by east–west trending gabbro dykes.

Coolgardie Group

The Coolgardie Group has a total thickness of 3.5 km (Fig. 27). The lowermost supracrustal unit is a thick (> 500 m) sequence of basalt flows (Burbanks Formation) containing thin, interflow sedimentary rocks and minor basaltic tuffs. Its base is only seen in contacts with younger gabbro and granitoid rock. A thick (500–800 m) layered gabbro (Three Mile Sill) intrudes the lower portion of the basalt sequence, generally at a flow boundary marked by sedimentary rock. A thin (150–200 m), feldspar-phyric basalt–dolerite and a felsic schist or clastic unit occur as distinctive marker horizons in the upper portion of the basalt sequence. The top of the Burbanks Formation is marked by grey shale which is generally intruded by a thin gabbro body (Golden Bar sill).

Overlying the basalt is a thick (> 600 m) sequence of komatiitic ultramafic flows (Hampton Formation) with minor interflow sedimentary rocks and a thin horizon (100–150 m) of high-Mg basalt.

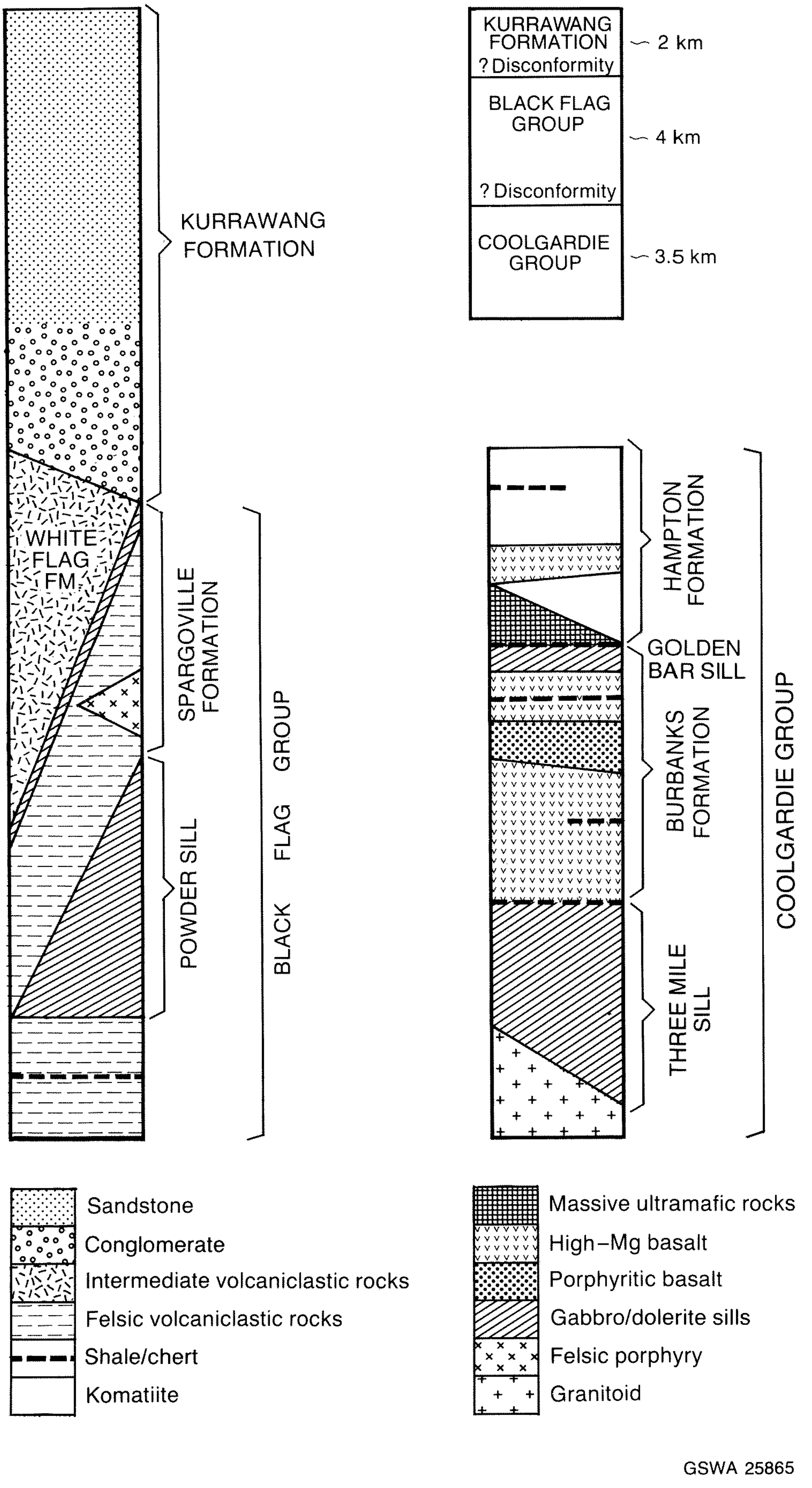


Figure 27. Proposed stratigraphic succession for the KALGOORLIE and YILMIA 1:100 000 sheets areas.

Black Flag Group

The Black Flag Group has a total thickness of about 4 km (Fig. 27) and its base is marked by a thin grey shale horizon which may indicate a disconformity. The group is overlain by a thick (1500 m), heterogeneous sequence of felsic volcaniclastic rocks, flows, intrusions, and minor sedimentary rocks (Spargoville Formation) which is intruded by a thin to thick (up to 1000 m) gabbro–dolerite sill (Powder Sill). These rocks locally grade up into a 50–1500 m sequence of intermediate volcaniclastic rocks and minor flows (White Flag Formation).

Kurrawang Formation

The Kurrawang Formation, formerly 'Kurrawang Beds', is a thick (about 2 km) sequence of conglomerate, conglomeratic sandstone, and sandstone which is apparently disconformable on the Black Flag Group.

Discussion

Discontinuities

Stratigraphic breaks within this succession are difficult to determine. Regional deformation has developed layer-parallel foliation and isoclinal folding, whereas local deformation has produced schistose lithological contacts within the succession.

Forman (1937a) separated his three lithologically similar volcano-sedimentary 'Series' with unconformities but the basis of this division is not clear. The change from 'Coolgardie Series' greenstones to 'Metasedimentary Series' whitestones was considered by McMath et al. (1953) to be a disconformity representing the cessation of volcanism and the onset of sedimentation with tectonic uplift. Glikson (1971b) regarded conglomerate in his 'Mungari Beds' and 'Kurrawang Beds' as deposits on unconformities within an evolving geosynclinal basin.

There are a number of minor stratigraphic breaks within the proposed succession but no major unconformities are recognized. The base of the Kurrawang Formation is erosional and a disconformity marks a change from a volcanic to a sedimentary environment.

There are two major chemical facies changes in the succession, the first where volcanism changes from mafic to ultramafic and another where it changes from ultramafic to felsic–intermediate. The breaks may be temporal and probably mark changes in the evolution of a broader volcanic process. They are marked by thin sedimentary horizons which also occur between flows throughout the Coolgardie Group and represent periods of quiescence rather than stratigraphic hiatuses.

The Spargoville Formation is predominantly volcanogenic with minor interbedded sedimentary rocks which are autochthonous deposits that flanked the volcanic edifices. Thin conglomeratic horizons are localized minor variations facies of the formation and do not represent erosional unconformities. A thin, but widespread, carbonaceous shale–chert horizon indicates at least one period of quiescence in the felsic volcanicity. The possible biogenic origin of carbon and textures in this horizon suggest a correlation with the stromatolitic horizon at nearby Kanowna (Grey, 1981).

Comparison with previous successions

The regional stratigraphies erected by Williams (1969, 1970) and Gemuts and Theron (1975) required the recurrence of lithotypes by repeated cycles of volcanicity. There is, however, a marked similarity between corresponding units of each cycle, including the location and type of marker horizons. The overall thickness of each 'cyclic' succession models is very large (> 40 km) and does not correspond to standard Archaean crustal models (Arndt, 1983; Condie, 1986; Nisbet, 1984). Further, the grades of metamorphism and their distribution pattern do not correspond to those expected from such depths of burial. The differences between similar members of each cycle are never significant and can be explained by local volcanic or depositional factors, or differences in metamorphic grade or deformation. It is concluded, therefore, that the cyclic-volcanicity model is invalid and that its numerous components are merely structural repetitions of a single, simple sequence of moderate thickness.

In the proposed succession, the Coolgardie Group is equivalent to the 'Coolgardie Series' (McMath et al., 1953) and 'Coolgardie Ophiolites' (Glikson, 1971b) but the internal sequence has been simplified. It is correlated also with the 'Kalgoorlie Series' of Forman (1937a) and the 'Kalgoorlie Succession' of Woodall (1965) but with reservations (see Table 5). The two mafic sills of the Coolgardie Group appear to correlate with the Golden Mile Dolerite and Williamstown Dolerite but no distinction is recognized at Coolgardie between the basalts separated by the lower sill. The location of the ultramafic unit presents a problem in that it is at the top of the Coolgardie Group and the bottom of Woodall's (1965) 'Kalgoorlie Succession'. This is a appears to be a difference in location, rather than an inversion of stratigraphy, as the successions are otherwise consistent. The extrusion of ultramafic lavas may be a regionally diachronous single event with the two levels being consanguineous, or there may have been two episodes of extrusion with limited regional extent. Alternatively, tectonic interleaving, possibly during D_1 thrusting, may have displaced the level of the ultramafic unit.

The Black Flag Group is equivalent to the 'Metasedimentary Series' (McMath et al., 1953) and the 'Black Flag Beds' (Woodall, 1965); the Spargoville Formation is correlated with the 'Black Flag Series' (Forman, 1937a) and the 'Mungari Beds' (Glikson, 1971b); and the White Flag Formation is correlated with Forman's (1937a) 'White Flag–Yindarlgooda Series'.

The overlying Kurrawang Formation is equivalent to the 'Kurrawang Beds' (Glikson, 1971b) and both the 'Kurrawang Series' and 'Kundana Series' (Forman, 1937a). It is correlated with the 'Merougil Beds' west of Kambalda (McCall, 1969).

Table 5. Comparison of proposed Coolgardie stratigraphy with Kalgoorlie stratigraphy

HUNTER (this report) *Coolgardie*	*WOODALL (1965)* *Kalgoorlie*
KURRAWANG FORMATION Conglomerate, sandy conglomerate, and sandstone	
WHITE FLAG FORMATION Intermediate tuff breccia and tuffs; minor dolerite sill	
BLACK FLAG FORMATION Felsic tuff breccia, tuffs, and intrusions; minor felsic flows, shales, and chert	BLACK FLAG BEDS Tuff, agglomerate, acid to intermediate lavas, slate, shale, greywacke, quartzite
POWDER SILL Major layered ultramafic–mafic intrusion	GOLDEN MILE DOLERITE Layered mafic sill; amphibolitic gabbro to granophyric quartz gabbro; intruded within basal Black Flag Beds
HAMPTON FORMATION Komatiite flows with minor shales; major basaltic flow horizon	
GOLDEN BAR SILL Minor dolerite sill	
BURBANKS FORMATION High-Mg basalt flows; minor mafic intrusions, shales and tholeiitic flows; porphyritic basalt–dolerite horizon	PARINGA BASALT High-Mg basalt, pillowed and massive; pelitic graphitic sedimentary rocks
THREE MILE SILL Major layered ultramafic–mafic intrusion; bounded by shale–chert horizon	WILLIAMSTOWN DOLERITE Layered ultramafic–mafic sill; intruded at base of, or within, the Paringa Basalt
	KAPAI SLATE Chert or silicified graphitic shale
?Basalt	DEVON CONSOLS BASALT High-Mg basalt
?Komatiite	HANNANS LAKE SERPENTINITE Ultramafic volcanics

Structure

Greenstones

A synthesis of early geological work at Kalgoorlie was presented by Forman (1937a), establishing a gross stratigraphic order which has changed little since. The earliest detailed structural interpretation was presented by McMath et al. (1953) for the Coolgardie area. They envisaged a thick, complex sequence which was tightly folded into a dome plunging north and south, and centred on the Coolgardie–Lord Bob area. This dome underwent cross-folding followed by granitoid intrusion. Sofoulis (1963) briefly referred to broad isoclinal folding along the eastern margin of BOORABBIN 1:250 000 sheet area.

Woodall (1965) subdivided the Kalgoorlie greenstones, detailing a succession of ultramafic to mafic rocks intruded by two major mafic sills and overlain by felsic volcaniclastic rocks. The regional structure was interpreted as a north-northwest trending pair of isoclinal folds.

The sequential stratigraphic interpretation of Gemuts and Theron (1975) followed previous ideas of broad isoclines modified by cross-folding but required numerous major faults to allow the juxtaposition of similar lithologies from different sequences.

Griffin et al. (1983) regarded the complex distribution of a restricted variety of lithotypes of the Kalgoorlie–Widgiemooltha area as due to multiple episodes of folding and faulting. This view of structural complexity was supported by Martyn (1987) for the Kalgoorlie region. A brief summary of the structure on YILMIA appears in Hunter (1989).

Swager (1989) has made a detailed structural study at Kalgoorlie which includes a correlation with other recent regional examinations of the Kalgoorlie–Norseman belt. The common theme of these studies is the recognition of an initial, recumbent fold–thrust sheet event followed by at least three phases of folding and wrench faulting.

The KALGOORLIE–YILMIA area may be divided into three structural regions where different aspects of the tectonism predominate. To the east, linear greenstone horizons resolve into mafic–ultramafic anticlinoria and felsic synclinoria. There has been a complex history of longitudinal attenuation and interleaving through pervasive shearing and compression. Around Coolgardie, the greenstones are arcuate, and both synclinoria and anticlinoria are within the mafic–ultramafic portion of the succession. There has been a similar complex history of deformation but the more open style is due to the structural influence of granitoid bodies and the development of confined shear zones. Between Coolgardie and Kalgoorlie, linear greenstones have a broad, open style of folding which is punctuated by narrow, upright shear zones trending subparallel to fold limbs. The shear zones are generally antiformal isoclines of schistose lithologies which are occluded along strike.

D_1: recumbent folds and ?thrusts

The earliest deformation recorded in the greenstones is the development of recumbent folds on a regional scale with possible associated thrusting. A pervasive, layer-parallel fabric, S_1, was developed during this event.

The scale of the folds is large, with a normal limb now exposed throughout the area. Hunter (1989) recorded shallow dipping beds of felsic volcaniclastic rocks with consistently overturned sedimentary structures at Bullabulling, 30 km west-southwest of Coolgardie. Eight kilometres southwest of Comet Hill, basaltic amphibolites and komatiites have moderate, undulating dips and subparallel fold axial planes overturned to the northeast. It is not clear whether this is a result of D_1 or a later event.

No thrust sheets have yet been unequivocally demonstrated in the field. However, sharp terminations of lithological trends and juxtaposition of equivalent fold hinges can be seen 1.5 km west of Londonderry gold mine, at Hampton Locality 59, and in the Nepean area. While they may be partly explained by axial-planar attenuation of upright folds, an interpretation as thrust planes is consistent with the proposed tectonic history of the area. A thin (1–2 m) horizon of talc schist occurs in otherwise massive rock within the lower portion of the basalt pile. It is parallel to layering and is regionally persistent. This enigmatic horizon may be a thrust plane.

D_2: northeast–southwest regional compression

Regional compression in a northeast–southwest direction produced open to tight, locally overturned folds with northwest to north-northwesterly trending axes. The trend of these folds is preserved at Comet Hill and in eastern YILMIA but no fabric has been recognized which can be assigned unequivocally to this phase of deformation. Fold closures in the Comet Hill area and around Gibraltar to the west suggest that D_2 folds had moderate southeast plunges and this may indicate possible southeasterly dip to the axial planes of D_1 folds.

Intrusion of the main 'within greenstone belt' granitoids occurred at this time, probably through partial melting at descending keel zones of folds.

D_3: southeast–northwest compression

The succeeding deformation was complex but appears to be consistent with crustal shortening in a northwest to southeast direction. This produced both folding and wrench faulting, depending on the prior attitude of the greenstones to the granitoids.

In the Coolgardie area and at Hampton Locality 59, greenstones were folded between competent granitoid masses. These refolds are characterized by sinuous, open to tight geometry and northeast-trending axes. Along granitoid margins with similar orientations, there are broad (50–100 m) zones of strong, upright foliation and attenuation attributed to reverse faulting.

A moderate to steep crenulation cleavage occurs in foliated komatiites in the Comet Hill area. Its orientation transverse to layering suggests it was developed during D_3 compression. Northeast of Grosmont, semi-brittle failure during D_3 deformation has produced a complex kink zone with north-northeasterly trending fault sets.

Along the eastern belts of YILMIA there was predominant development of shear zones and consequent slicing of the succession. From Kunanalling through Karramindie and Logans Find to Larkinville, there is a marked interjection and lensing of lithologies which is attributed to the development of broad zones of anastomosing spaced shears and local mylonite (Kunanalling Shear Zone). A second major shear can be traced parallel to the greenstones which run from Blue Funnel via Saddle Hills to Larkinville (Mungari Shear Zone*). This shear is marked by a 10–20 m core of highly schistose to mylonitic rock (commonly silicified) and a 10–30 m margin of schistose to brecciated country rock. The bedding orientations of surrounding units are discordant to the shear, suggesting significant displacement and/or volume loss. Limited field evidence indicates that minimum sinistral offsets of the order of several kilometres were produced on these shears.

A number of hook-shaped or looped folds are evident in close proximity to the shear zones. Swager (1989) has described similar folds at Kalgoorlie as en-echelon wrench folds. It is not clear from the field relations whether these folds were formed by a similar mechanism or through D_4 tightening of D_3 refolds. The folds southwest of Karramindie and north of Spargoville have a dextral sense of rotation and their margins towards the Depot Granodiorite are loci of wrenching. If these are related to the Kunanalling and Mungari* Shears, then they must have been generated by subordinate antithetic shears.

D_4: northeast–southwest regional compression

The last period of major deformation resulted from regional compression in a northeast–southwest direction. This produced tightening of earlier north-northwest trending structures and 'wrap-around' of structures adjacent to competent granitoid masses (such as the Depot Granodiorite). The fabrics from this event are difficult to distinguish because of the dominant north-northwest orientation of the greenstone belts and layer-parallel S_1. However, D_4 cleavage can be found at the hinge zones of refolds and cutting across regional trends in the Londonderry–Burbanks area. Foliation and reverse faulting at granitoid margins may be associated in part with this event.

A shear zone runs from Nepean, passing southeast of Londonderry goldmine to Burbanks and on to Tindals, with minor offsets by later northwest faults. This has been interpreted as a dextral wrench which, for most of its length, has a northeasterly trend. A swarm of faults running from Black Flag Station, via Mount Burges Station, and through the Coolgardie townsite also has this orientation. In the absence of any age relationship between this shear and the Kunanalling and Mungari* Shears (D_3), it cannot be asserted whether this is an antithetic shear or a discrete wrench orientation of later generation (D_4).

A series of faults perpendicular to all greenstone belts appear to cut features of all deformation events. They are commonly represented by linear drainage features at lithological offsets and, in places, have acted as conduits for the 'Yilgarn Dyke Suite' (*Edy*). These faults represent a phase of rigid block adjustments following the major deformation event(s) of D_4.

Granitoids

Within greenstone belts

The granitoids have had a complex history of intrusion and deformation. Their stoped margins and contact metamorphic aureoles are discordant to, and therefore post-date, layer-parallel S_1 foliation; thereby, magmatic intrusion during D_2 is inferred. Deformation is confined to narrow marginal zones where non-lineated foliation is parallel to the pluton margins. The interiors of the plutons are structurally isotropic, while structural elements of the host greenstones wrap around each pluton. The D_3 deformation probably imparted a marginal foliation to the competent granitoid masses, after consolidation of the granitoids. During the subsequent D_4 compression, the more ductile greenstones were deformed around the relatively rigid granitoids.

* Now renamed to Zuleika Shear (Zone).

Between greenstone belts

While the relative ages of emplacement of these granitoids can be deduced from field observations, there is no direct evidence to relate the timing to the deformation events within the greenstones. The granodiorite and tonalite gneiss (*Anst*) in YILMIA may represent a pre-greenstone sialic basement. Field evidence suggests that banded gneiss (*An*) is the product of deformation of such a basement. Radiometric age determinations (e.g. McCulloch et al., 1983) indicate that this deformation event occurred close to the time of deposition of the supracrustal rocks and may, therefore, be related to D_1. The arcuate trends of gneiss outcrops are attributed to fold interference patterns.

The later major granitoids, the Burra (*Agph*) and Woolgangie (*Agr*) Monzogranites, have good magmatic intrusive contacts with their precursors. Foliated and inclusion-rich facies of these granitoids comprise arcuate zones confined to the margins of apparent plutons, while the interiors of the plutons are homogeneous. The foliations are vertical and have no mineral lineation. It is proposed that these features in the Burra Monzogranite indicate emplacement by a mechanism of 'ballooning tectonics' (Ramsay, 1981; Wikstrom, 1984). It was probably intruded in sheeted form into the gneissic basement. Woolgangie Monzogranite intruded parallel to the margins of the Burra Monzogranite, inheriting some of its heterogeneities. Regional compression (?D_2 or ?D_4) folded the sheeted complex about northwest-southeast axes to produce the current orientation of lithologies.

Archaean geology of selected regions

In this section, selected regions of KALGOORLIE and YILMIA are discussed in terms of their degree and quality of outcrop, rock types present, and history of deformation. Locality names used are shown in Figure 1 or listed in the locality index (Appendix).

Coolgardie region

The Coolgardie region contains extensive, continuous exposure of moderately weathered rock in ranges of low hills. Mafic to ultramafic flows, mafic sills, and minor sedimentary rocks outcrop in arcuate units which are separated locally by slightly discordant, ovoid granitoid plutons. All units have steep dips and the rocks are metamorphosed at upper greenschist to lower amphibolite facies.

The units have a strong parallelism which can be traced over tens of kilometres and there is a broad regional symmetry. There are no significant distinctions between units of similar lithology across the region. The apparent width of units increases away from granitoid margins (e.g. north of Coolgardie) and at fold hinges (e.g. at the Surprise mine) but diminishes in the vicinity of shear zones (e.g. east of Londonderry mine). Along the northwestern margin of the Calooli Monzogranite there is some slicing, attenuation, and interleaving of units.

A swarm of north-northeasterly faults cuts the region and a shear zone with similar orientation extends from Nepean to Tindals, east of Londonderry and Burbanks gold mines. West- to northwest-trending faults perpendicular to the greenstone trends are also abundant in the region.

The succession at Coolgardie is interpreted as simple and is represented by the Coolgardie Group. The repetition and parallelism of units is a result of tight isoclinal folding, whereas broader apparent widths result from more open isoclines with parasitic folds. In the vicinity of Mount Burges, the broad exposure of ultramafic rocks is inferred to have resulted from doming over a concealed granitoid pluton.

Kunanalling Shear Zone

A curvilinear tectonic zone, the Kunanalling Shear Zone, extends from Kintore to the southeast corner of YILMIA but is inferred to extend further to the south and to the north. There is an heterogeneous distribution of lithologies within this zone which ranges from a few tens of metres to 2 km wide. Where the zone is at its widest (e.g. south of Kintore), it comprises mafic, ultramafic, and minor felsic rocks which contain broadly spaced, upright bands of strong foliation. Primary textures are generally preserved in these rocks but are progressively destroyed near foliated bands. Where the zone is narrower (e.g. 3.5 km east of Northlander), it is composed of interleaved units of felsic to ultramafic schist with minor enclaves of unfoliated precursors. Schistosity is parallel to the tectonic zone and subparallel to layering, with moderate to steep dips. A steep, down-dip lineation occurs locally, particularly close to granitoid margins.

Northwest of Karramindie Soak, the shear is represented by a zone of mylonite, up to 10 m, at the base of the felsic volcaniclastic unit, while in the area from west of Horse Rocks to Larkinville, the tectonic zone is wide and ill-defined, comprising broadly spaced anastomosing bands of strong foliation which occlude and slice the stratigraphy.

Tight folds within the tectonic zone near the Last Chance and Star of Fremantle mines are interpreted as en-echelon folds (Wilcox et al., 1973) which have been tightened subsequently. They are associated with conjugate strike-slip faults which pass the Blue Bell and Sydney Mint mines. Swager (1989) has also interpreted larger scale folds north of Kunanalling as en-echelon folds.

The tectonic zone is interpreted as a shear zone with predominantly sinistral movement but the amount of offset is unclear. The ultramafic units at Northlander and north of Kunanalling are equivalent; so if their separation is purely due to lateral offset on the shear, then the displacement would be of the order of 5–6 km. Some late vertical movement in the shear zone is indicated by the presence of down-dip lineations. If the folds north of Kunanalling are en-echelon to this shear zone, then they must be of later generation than those recorded above, this suggests a protracted history of movement on the shear.

Kunanalling to Black Flag

Northwestern KALGOORLIE contains intermittent outcrop of deeply weathered rocks separated by broad tracts of surficial deposits. Exposure is good at breakaways and lake margins but, otherwise, it consists of subcrop and rubble-trains mantling low rises. A range of rock types from ultramafic to felsic are present and the full succession from the Burbanks Formation to the Kurrawang Formation is represented.

North of Kunanalling, refolded isoclines of ultramafic to felsic rocks lie between the Kintore Tonalite and the Powder Sill (Fig. 1). The structure here is complex, with fold axes being offset and juxtaposed. Gabbro occupies the core of an anticlinal refold 1.3 km west of Telegraph Dam, but felsic volcaniclastic rock occupies the core of a synclinal refold 2 km north-northeast of the Premier mine. Complementary anticlinal axes are represented by highly deformed mafic and ultramafic rocks 1 km north and 2.5 km northeast of the Premier mine. The northernmost closure of this fold group, northeast of Kintore, is discordant to adjacent trends and is separated by a synthetic strike fault bounding the eastern margin of the Kintore Tonalite.

The Powder Sill occupies an open, south-plunging syncline located between the Kunanalling Shear Zone (west) and the Mungari Shear Zone* (east). The western limb is oblique to the trend of the Kunanalling Shear Zone which intersects it at Cane Grass Swamp. The eastern limb is poorly exposed but aeromagnetic data suggests that it is truncated west of Kundana. The sill intrudes poorly exposed felsic volcaniclastic rocks which are highly deformed adjacent to the shear zone. The open, brittle style of deformation of the Powder Sill contrasts with regions immediately to east and west. This may be due to the relative physical competence of the quartz gabbro or to its location in a low-strain domain between the two major shears. Alternatively, the area may be a pressure shadow against a concealed granitoid pluton.

A narrow complex zone of mixed lithologies extends from Zuleika to Kundana. Ultramafic rock at Zuleika forms a south-plunging anticline which extends under Broad Dam to Blue Funnel where it is attenuated in the Mungari Shear. Pods of this ultramafic unit are concealed at Enclosure Dam but re-emerge west of Kundana. The intervening rocks are felsic to intermediate volcaniclastic rock and dolerite. This zone is interpreted as a disrupted anticline which has been tightened between the Powder Sill and the Mungari Shear. The fold has an undulating hinge line which may have been generated by deformation en-echelon to the Mungari Shear.

* Now renamed to Zuleika Shear (Zone).

Continuity of the units has also been offset by a swarm of north-northeasterly cross-faults.

Terrigenous sedimentary rocks of the Kurrawang Formation occupy a 4 km wide, northwest-trending syncline centred on Monument Dam. The lower conglomeratic horizon is thicker on the western limb but both limbs diminish northwestward due to facies transitions and some degree of shearing. Apparent duplication of the magnetic BIF-pebble horizon 2 km west of Monument Dam is attributed to tectonism marginal to the Mungari Shear Zone.

A broad tract of intermediate volcanic and volcaniclastic rocks underlies the Kurrawang Formation to the northeast. The succession of volcanogenic units, which have moderate to steep westerly dips, is best exposed west of White Flag Lake. The lower boundary of the Kurrawang Formation is intruded by a thin dolerite sill.

Southeast of Crown Dam, fine-grained felsic volcaniclastic rocks of the Black Flag Formation form the core of a minor anticline or monocline which has a shallow southeasterly plunge. A thin, carbonaceous chert horizon can be traced throughout this area, defining a series of parasitic folds to the minor anticline. Towards the northeastern limit of outcrop, parasitic folds become tighter and there is localized, intense northwesterly shearing.

From Town Dam to Mount Pleasant, a thick sequence of basalts, dolerites, and gabbros forms an open-style anticline with a shallow southeasterly plunge. Porphyritic basalt–dolerite underlies the Black Flag Formation but contact relationships indicate that the formation was intruded at the base, penecontemporaneous with deposition. A thick layered gabbro (Mount Pleasant Sill) intrudes the underlying high-Mg basalts and is itself intruded by felsic porphyry and granitoid rock.

A suite of northeast-trending faults, including the economically significant Black Flag Fault, traverses the area from Northlander to Mount Pleasant and post-dates the Kunanalling Shear Zone. It is a continuation of a suite with similar orientation which passes through the Coolgardie area.

Northeast Kalgoorlie region

The northeast portion of KALGOORLIE region contains poor exposure of generally lateritized rock in breakaways, playa margins, and some low rises. Outcrops tend to be isolated with little lateral or strike continuity. The geology of this region has been discussed in detail by Keats (1987).

There is a feldspar-phyric monzogranite in the northeast corner of KALGOORLIE which is best exposed near Kanowna Homestead. A narrow belt of basalt, dolerite, and komatiite follows the boundary of this granitoid, trending south and eastward through Mount Eddy. A similar belt of mafic to ultramafic rocks follows a subparallel trend from 2.5 km west of Mount Eddy to the eastern sheet boundary, 2 km south of Ten Mile Dam. The belts are flanked by felsic volcaniclastic rocks. There is a general increase in the degree of foliation northward with a corresponding decrease in unit width.

Low-level aeromagnetic data reveals that these two belts are continuous and narrow with a slight broadening southward (Aerodata, 1983) . The mafic–ultramafic belts are interpreted as anticlinoria, and the felsic belts, as synclinoria. There has been strong longitudinal shearing which increases in intensity northward.

The western limit of this region is marked by the 'Parkeston Dyke' (Fig. 2) which is a narrow negative magnetic anomaly extending from the Mount Pleasant copper mine to east of the Kalgoorlie township. The concealed dyke is 50–150 m wide and drill intersections reveal compositions from mafic rock to granophyric gabbro (Keats, 1987).

Mungari Shear Zone

A curvilinear tectonic zone, the Mungari Shear Zone*, extends from Blue Funnel in northwestern KALGOORLIE to Larkinville in southeastern YILMIA but is inferred to extend further to the north and to the south. There is an heterogeneous distribution of lithologies within this zone which ranges from a few tens of metres to 500 m wide. Where it is at its widest (e.g. northwest of Kundana), the shear zone comprises ultramafic to felsic rocks which contain broadly spaced, upright bands of strong foliation. Primary textures are generally preserved in these rocks but are progressively destroyed near foliated bands. Where the zone is narrower (e.g. south of Spargoville) it comprises felsic to ultramafic schist and local mylonite. Anastomosing schistosity lies parallel to the tectonic zone and subparallel to layering, and has moderate to steep dips. A steep, down-dip lineation occurs locally, particularly close to granitoid margins.

There is intermittent exposure of the Mungari Shear Zone between Blue Funnel and Kundana. It lies between the Powder Sill and the Kurrawang Formation as a narrow, complex zone of mixed lithologies in a highly attenuated anticline. At Blue Funnel, conglomerates of the Kurrawang Formation are juxtaposed with mafic and ultramafic schists, whereas at Kundana, spaced zones of intense shearing are present in felsic and intermediate volcaniclastic rocks as well as in conglomerate.

The northern extension of the Mungari Shear Zone beyond Blue Funnel is unclear. The western conglomeratic limb of the Kurrawang Formation syncline is absent, and sandstone is juxtaposed with felsic volcaniclastic rock 3.5 km east of Zuleika. However, at Zuleika the boundary between komatiite and felsic rocks is strongly sheared. It is inferred that the shear branches in this area; one branch underlies the course of the linear, northwest drainage channel and the other trends northwesterly through Zuleika.

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* Now renamed to the Zuleika Shear Zone.

At the western end of Red Lake, the Mungari Shear cuts the western limb of an anticline which forms the peninsula. Along the western boundary of the Saddle Hills belt and the eastern boundary of the Depot Granodiorite, it forms a narrow zone of ultramafic to felsic schists.

The Mungari Shear Zone between Spargoville and Larkinville is narrow and marks the western boundary of the Holmans mafic–ultramafic belt. The trends of mafic units and interflow sedimentary rocks are truncated by the shear. Bedding in the felsic rocks to the west is discordant to the shear orientation but tight drag folding develops close to the shear. Excavations at the Spargoville reservoir reveal continuous exposure of a tectonized boundary between felsic volcaniclastic rocks and basaltic rocks. From Spargos Reward to Holmans the shear is manifest in a silicified, subvertical mylonite zone where several metres of flaggy, fuchsitic quartzite schists form an upright, continuous band of outcrops. West of this zone, anastomosing shears pervade the felsic rocks, whereas to the east, prase-bearing silicified ultramafic schists grade over tens of metres into spinifex-textured komatiites. Basalt, dolerite, and shale–chert horizons are strongly foliated and silicified at the shear but brecciated on the periphery.

The shear is also exposed north of Larkinville where fuchsitic quartzite schists and slates separate felsic and ultramafic rocks.

There is no unequivocal evidence to indicate the sense or magnitude of movement on the Mungari Shear but several features suggest it was sinistral. At the Blue Funnel mine there are mineralized fractures indicating some sinistral and west-side-up movement on the shear (C. Swager, pers. comm., 1986). The orientation of ultramafic pods just east of the Powder Sill may be a relict of en-echelon folding marginal to the shear which could also be attributed to sinistral movement.

Gunga to Gibson–Honman Rock

The region from Gunga to Gibson–Honman Rock contains intermittent exposure of moderate to highly weathered rock in breakaway pediments and low southeast-trending ridges. Felsic volcaniclastic rocks and Kurrawang Formation sedimentary rocks are dominant but there are narrow intercalations of mafic to ultramafic flows and intrusions. The units have limited continuity but are readily correlated with similar lithologies to the northwest and southeast. It is a structurally complex region but good younging evidence in the felsic volcaniclastic rocks provides reasonably good understanding of diachronous folding and faulting.

From Gunga to Perron Dam there is a tightly folded sequence of felsic volcanic and volcaniclastic rocks containing penecontemporaneous gabbroic intrusions. The Kunanalling Shear Zone is marked by a narrow belt of mafic to ultramafic schists passing through Drydens and Mount Robinson. This represents a tectonized infold of the Coolgardie Group rocks.

A series of more open folds in felsic volcaniclastic rock occurs between Perron and Blue Dams but are truncated by a set of north-trending upright faults.

The Mungari Shear Zone* passes 1 km west of Blue Dam and extends into the western part of Red Lake. It represents an anticlinal infolding of the underlying Coolgardie Group and comprises ultramafic to mafic lavas and intrusions.

North of Mungari, a poorly exposed anticline was revealed by multispectral remote-sensing (Rothery et al., 1986) and confirmed by tracing persistent carbonaceous shale and dolerite horizons.

Felsic and intermediate volcaniclastic rocks with carbonaceous shales are intruded by dolerite northeast of Blue Dam. The general structure is an east-facing steep fold limb but there are numerous intervening minor folds and faults and some overturned bedding.

Between Red and White Lakes the Kurrawang Formation occupies an open-style syncline which closes beneath the playa system. The formation is not recognized in the southeast of KALGOORLIE or in YILMIA but is correlated with the ‘Merougil Beds’ on LAKE LEFROY 1:100 000 sheet (Griffin, 1990a) . The fold closure is complicated by northwesterly faulting but pebble horizons in sandstone and conglomerate delineate the sinuous bed forms. Beds on both limbs have moderate to steep dips with normal younging.

Underlying felsic volcanic and volcaniclastic rocks between Seven Mile Hill and Gibson–Honman Rock are strongly folded, and younging reversals are common between the widely separated outcrops.

Kalgoorlie–Boulder

Natural exposure in the north of Kalgoorlie–Boulder region is poor and rocks are generally lateritized. However, there has been extensive exploratory drilling and in the Kalgoorlie–Boulder town area, abundant mines provide good exposure of relatively fresh rock. In the southern half of the region, there are discontinuous outcrops of lateritized to moderately fresh rocks in low ridges and valleys. Lithologies range from komatiite, through high-Mg basalt, dolerite, felsic volcaniclastic rocks, to sedimentary rocks. This area has been the focus of great geological debate since gold was discovered there in 1893. More recent, detailed discussions of the geology and structures have been given by Griffin et al. (1983), Keats (1987), and Swager (1989).

In the Kalgoorlie–Boulder townsite, a complex greenstone belt has a prominent hook form, and is bounded to the east by the Parkeston Dyke and to the west by the Boulder Fault. The stratigraphy described by Keats (1987) is similar to that at Kambalda (Gresham and Loftus-Hills, 1981), but differs from that at Coolgardie where komatiite occurs uppermost in the

* Now renamed to the Zuleika Shear Zone.

mafic–ultramafic pile. It is not clear whether this indicates restricted facies and diachronous volcanism or displace-ment of elements of the sequence by thrusting. The belt represents a regional anticline but there is evidence of refolding of isoclines (Keats, 1987) and of early thrusting (Swager, 1989).

From the Horans Dams in the north to the nickel smelter in the south, there are elongate, but discontinuous, outcrops with some across-strike continuity. The stratigraphic relationships are equivalent to those at Kalgoorlie but they have been considerably complicated by faulting and shearing (Griffin et al., 1983; Keats, 1987) The mafic–ultramafic rocks occupy structurally modified anticlinoria, whereas the intervening felsic volcaniclastic rocks occupy structurally modified synclinoria.

Nepean to Karramindie

In the Nepean to Karramindie region, three mafic–ultramafic belts occur with 'thumbprint-like' lithological trends. The quality of outcrop varies from moderate at Nepean to good to the southwest of Change Creek but ubiquitous costeans provide reasonable exposure. The low arcuate ridges are composed of lower amphibolite facies rocks which are generally well preserved; the intervening ground contains occasional outcrop of felsic volcaniclastic and granitoid rocks.

Nepean area

The Nepean nickel mine lies in a 2 x 5 km belt of gabbro, basalt, komatiite, and minor sedimentary rock. Aeromagnetic data reveals a narrow, but continuous, connection between the Nepean belt and the Coolgardie belt at the Londonderry pegmatite mine.

A layered gabbro sill intrudes the base of a thick basalt sequence at the level of a sulfidic grey shale horizon. The basalts are high-Mg in character with locally good pillows and ocellar structures. In the upper portions of the basalt unit there are two thin, but persistent, marker horizons — a feldspar-phyric basalt and an auriferous, felsic clastic–porphyry association. Komatiites with good spinifex-textured sequences are found throughout the belt.

The succession is identical to that mapped at Coolgardie. The structure in the western part of the belt is a tight isoclinal synclinorium with locally intense axial-planar shearing and numerous cross-faults. The eastern part of the belt has a more open style of folding. There is good structural control on the younging direction of the gabbro sill and underlying shale which suggests that a north-plunging syncline lies to the east of the Nepean gold mine. Southeast of the mine and along the eastern margin of the belt, an ultramafic unit appears to lie at the base of the succession. It is not clear whether this is a true, but enigmatic, depositional location or whether the mafic pile has been thrust over the ultramafic rocks. The eastern and western portions of this belt are separated by a major shear zone which is inferred to be a continuation of the shear to the east of the Londonderry gold mine.

Northeast Nepean area

A region of poor outcrop to the northeast of Nepean is underlain by granitoid rock; a sinuous greenstone belt containing basalt, gabbro, felsic volcaniclastic rocks, and minor ultramafic rocks is well exposed in a series of ridges 15 km to the east-northeast. Basalt ranges from fine to medium grained, and contains good pillow structures and a feldspar-phyric unit which provides a distinctive, persistent marker horizon. The unit displays flow orientation of feldspar grains at chilled contacts and a (?metamorphic) grain coarsening in upper portions. A major, layered gabbro sill is subconcordant and bounded by grey shales. Thin, discontinuous units of felsic volcaniclastic rocks are common throughout the belt. The ultramafic unit is a poorly exposed tremolite–chlorite–talc rock with no primary textures preserved. An equigranular granitoid lies to the southeast of the greenstone belt.

Younging evidence on the periphery of this belt is consistently inward, indicating a simple syncline and anticline to the west and east respectively. However, the eastern limbs are complex and highly attenuated, and there are indications of refolding towards the south of the belt. Comparison with the adjacent greenstone belts suggests that these folds may be refolded isoclines.

Karramindie Soak to Horse Rocks

A 3 x 20 km greenstone belt extends from northwest of Karramindie Soak to a point 8 km southwest of Horse Rocks. There is good exposure of lower amphibolite grade rocks in low ridges where mafic to ultramafic rocks form discontinuous subparallel units; close to the Coolgardie–Esperance Highway there is a fold closure of mafic to ultramafic rocks. Felsic rocks occur in low, moderately exposed ground to the east and west of the belt, and occur as rare thin units within the belt which is cut by a swarm of west-southwest cross faults, some of which contain dolerite dykes.

Komatiite with well preserved spinifex textures occur in the fold closure to the north, whereas to the south partly preserved komatiite units alternate with ultramafic schists. Basalts contain good pillow structures and thick flows with medium- to coarse-grained centres. Thick gabbro sills are layered and bound by grey shale horizons. The felsic volcaniclastic rocks have well preserved sedimentary structures. Granitoid rock and pegmatite are abundant in the southern part of this belt, both as concordant sheets and small discordant stocks.

The eastern boundary of the mafic–ultramafic belt is marked by a major shear which is narrow and mylonitic about 3 km northwest of Karramindie Soak. South of the Coolgardie–Esperance Highway it is marked by a narrow zone of mafic–ultramafic schist bordered by brecciated rocks and, in the southern part of the belt, the shear becomes dispersed as spaced bands of intense foliation separated by undisturbed lithologies. It is inferred to be an extension of the Kunanalling Shear Zone.

Structural data indicates that the belt is an overturned anticline with a steep (overturned) hinge line. This is composed of isoclinally folded units which have been refolded about a north–south axis and truncated against the shear.

Saddle Hills

The northwest-trending Saddle Hills contains a 5 x 15 km belt of gabbro, basalt, komatiite, and minor sedimentary rocks. There is good exposure of reasonably fresh rocks which have been metamorphosed to lower amphibolite facies. The belt is flanked to the northeast and southwest by low ground containing scattered outcrop of lateritized felsic volcaniclastic and intrusive rock.

In the belt, there is a simple lithological symmetry which becomes progressively more complex from north to south. Thickness of similar units decreases from east to west together with an increase of intensity of foliation. The core of the belt contains thinly bedded felsic volcaniclastic rocks which are poorly exposed, and are bounded to the east and to the west by a thick sequence of high-Mg basalt containing interflow sedimentary rocks. The lower boundary of the basalts was intruded by a thick, layered gabbro sill in the central and southern parts of the belt. Komatiite with well preserved spinifex-textured sequences and pillows occurs along the eastern margin of the Saddle Hills, whereas occluded units of komatiite with felsic and mafic rocks along the western margin become progressively attenuated and more schistose northward and westward.

A wrench fault extends from the southern Saddle Hills, 2.5 km southwest of Survey Dam, to the boundary of the gabbro sill, 500 m southwest of Mount Marion. A tectonized shale unit which separates high-Mg basalt and felsic volcaniclastic rock 2 km northwest of Mount Herbert is inferred to be the northerly continuation of this fault. A major shear zone marks the western boundary of the Saddle Hills belt against the Depot Granodiorite and felsic volcaniclastic rocks.

The eastern part of the Saddle Hills belt contains good younging evidence from lava pillows, mineral grading and sedimentary structures, which are progressively destroyed westward. The belt is interpreted as a doubly plunging anticline which is complicated by parasitic folding, faulting, and shearing. The clastic rocks occupying the core of the anticline may have been deposited before the overlying basalts or they may be equivalent to the Black Flag Formation and the basalts ?thrust faulted over them. On the southwestern margin, the strips of mafic, ultramafic, and felsic rocks are consistent with slicing and occlusion of the west limb parallel to the orientation of the marginal shear zone (Mungari Shear Zone).

Spargoville to Larkinville

From Spargoville to Larkinville, four linear belts of mafic to ultramafic lithologies form ridged topography with reasonably good exposure. They trend from north to northwest and rarely exceed 2 km in width over a strike length of 25 km. Felsic rocks occupy the intervening ground but are poorly exposed in breakaways.

The Logans Find belt comprises narrow units of basalt, gabbro, and komatiite which are offset by abundant west-southwest faults. The units are commonly occluded along strike and there are anastomosing, spaced bands of intense foliation. A thick gabbro unit becomes dominant towards Larkinville. Detailed aeromagnetic data (Aerodata, 1983) indicates that this belt has a continuous, but attenuated, northward extension linking with the Karramindie belt. The Logans Find belt is interpreted as an anticline with a gentle northerly plunge. The west-southwest faults give progressive downthrow to the north, exposing higher levels of the succession.

From Larkinville to Spargoville, via the Twenty Grand mine, a narrow belt is dominated by komatiite and tremolite–talc–carbonate schists. Ferruginous or cherty shale bands are common, particularly in the centre of the belt, and there are narrow pillow basalt units. Conflicting younging criteria and poor correlation of units along strike are attributed to intense slicing of the sequence and attenuation or repetition of some horizons. This belt represents the remnants of an anticlinorium exposed closer to its hinge line than the Logans Find belt. North of Larkinville, a narrow strip of fuchsitic schist and cherty metasedimentary rocks represents the locus of shearing in a downfaulted slice.

A similar sequence occurs in the Holmans belt. Within the komatiite unit a thin basaltic horizon defines a steeply plunging isoclinal fold closure. This displays spectacular amphibolitized pyroxene spinifex texture. Persistent, but thin, ferruginous grey shales and cherts are traceable from limbs in the south to parasitic flexures near the highway in the north, before being truncated by axial planar slicing and cross faults. Shearing in this belt is confined to specific locations rather than widespread attenuation. The western limb is truncated by a narrow (< 10 m) shear zone which is locally mylonitic. The eastern limb is equally attenuated but without the development of an isolated shear; instead, narrow high-strain horizons are developed in dunitic layers of komatiites and in interflow sedimentary rocks. The belt is interpreted as an anticline with isoclinal minor folds.

Northward from Andrews Shaft is a complex mafic–ultramafic belt bearing one of the few nickel deposits on YILMIA which has been mined. Komatiites have good spinifex-textured sequences, while pillow and ocellar structures are well preserved in high-Mg basalts. Interflow sedimentary rocks are abundant and commonly show complex, secondary drag-folding. Andrews Shaft is sited on an asymmetric anticline which is slightly overturned to the east and closes 4.5 km east of North Dam (Andrews, 1975; Hancock et al., 1971). The komatiitic unit which trends southeast from there represents a tightening ?minor synclinal closure, while the mafic ridge 500 m to the east is part of another anticline.

Structural complexity increases towards the eastern side of the belt and the northern end swings eastward, forming a hooked, anticlinal refold closure. This geometry may be associated with the strong deformation on the eastern side of the belt, indicating that a zone of dextral shearing may occur to the east on the LAKE LEFROY 1:100 000 sheet area. The belt is generally anticlinal but parasitic or minor folding and plunge reversals are common. Superimposed on this structure are axial-planar shearing and west-southwest trending cross-cutting faults.

Separating the four mafic–ultramafic belts are generally broader tracts of felsic volcaniclastic and sedimentary rocks with minor intrusions. In contrast to the adjacent anticlinoria, these are poorly exposed regions of deeply lateritized rocks. Genetic interpretations of these rocks, therefore, rely heavily on field observations.

Northwestward from Larkinville, a 3 km wide felsic belt extends as far as the Spargoville–Connolly telegraph line where the clastic rocks occur in a feather-edge margin to the Depot Granodiorite. Sheeted intrusions of microgranite, aplite, and pegmatite lie parallel to bedding, and occupy up to 50% of outcrop. Larger, discordant bodies of pegmatite occur north and northwest of North Dam, and an enigmatic felsic body occurs 4 km southwest of Spargos Reward. This body appears to be a sub-volcanic intrusion which has been repeated by folding and cross faulting.

Throughout this belt, exposed sedimentary structures show younging mainly to the east, whereas regional evidence indicates the presence of a syncline. Minor folding, which is common, is usually accompanied by axial-planar shearing. Faults with northwesterly trend and steep to moderate westerly dips are also present. It is deduced, therefore, that pervasive minor folding has been modified by preferential attenuation of west-younging limbs.

The Spargos Reward belt contains a range of felsic volcaniclastic rocks, from proximal tuff breccias to distal tuffs interbedded with epiclastic sedimentary rocks. The complexity of outcrop distribution is, in part, facies related and, in part, structurally controlled. Abundant facing reversals across strike indicate a tight synclinorium with a moderate northerly plunge.

A similar sequence of mixed felsic volcaniclastic rocks occurs along the eastern boundary of YILMIA. The belt comprises a tight synclinorium in the Reid Dam–Andrews Shaft area, which broadens northward, and there is a major anticlinal closure just east of the map boundary.

In summary, the Spargoville to Larkinville region consists of four mafic–ultramafic and three felsic belts which are linear, narrow, and structurally complex. There is marked lithological symmetry both within and between belts, and most belts converge along strike. There is strong similarity in lithology and stratigraphy between belts of equivalent type. Mafic–ultramafic belts constitute anticlinoria, and felsic belts, synclinoria.

It is concluded that all the mafic–ultramafic belts are equivalent, simple successions which are correlated with the Coolgardie Group. The felsic belts are also equivalent successions but with more facies diversity, and are correlated with the Black Flag Group. Isoclinal folding, and transverse and axial-planar faulting have produced complex repetitions of units and groups throughout the area. Two major shear zones pass through this region. The Kunanalling Shear is dispersed in the Logans Find belt, whereas the Mungari Shear* is confined to the western margin of the Holmans belt.

Three kilometres north of Spargoville an arcuate belt of gabbro, basalt, and komatiite lies on the southeast margin of the Depot Granodiorite. It is bordered to the east and west by felsic volcaniclastic rocks and is interrupted by a group of southwest-trending faults. Parasitic folding is abundant in the main shale horizon and is traceable around the fold closure. This belt is correlated with the mafic–ultramafic belt to the south which contains the Twenty Grand mine. It comprises an anticline with southwesterly plunge which has been refolded about a more northerly axis to generate the hook form. The geometry of this fold complements that to the northwest of Horse Rocks and may have been generated by the same couple of shears wrapped around the margin of the Depot Granodiorite. Its orientation and more open form are due to its location in a low-strain shadow at the end of the granitoid body.

Southwest Yilmia

The southwestern half of YILMIA contains isolated, but evenly distributed, outcrops of granitoid rock set in tracts of sandplain and colluvium. The outcrops are generally small (< 500 m) pavements of reasonably fresh rock, although larger (> 1 km) rounded hills are also present.

The oldest granitoid unit in this region is a streaky gneiss (*Anst*) which is poorly exposed 10 km west-northwest of Larkinville. The streaky gneiss also forms part of the banded gneiss complex (*An*) which is well exposed near Connolly Siding, and extends in an annular tract through Durgulyie Rock and Quairnie Rock to Yilmia Siding. A voluminous, feldspar-phyric monzogranite, the Burra Monzogranite (*Agph*), lies mostly to the west of the track from Nepean to Ten Mile Rocks. It has a stoped, magmatic contact with banded gneiss and a narrow, foliated, heterogeneous marginal zone. The interior of the body is generally homogeneous. An equigranular, recrystallized granitoid, the Woolgangie Monzogranite (*Agr*), forms an ovoid body southeast of Nepean where it is surrounded by banded gneiss.

* Now renamed to the Zuleika Shear.

The relative ages of these granitoids is well constrained by cross-cutting relationships and the presence of xenoliths (Hunter, 1989). However, the absolute age of emplacement and the relationship to deformation of greenstones remains equivocal. The streaky gneiss (*Anst*) may represent sialic crust on which the greenstones were deposited. The banded gneiss was produced by deformation of streaky gneiss which had been intruded by mafic-rich granitoid dykes. This may correlate with early stages of greenstone belt deformation. It is inferred that the later granitoids (*Agph, Agr*) were intruded in sheet form, probably during the later stages of greenstone deformation. Textural evidence indicates that these two granitoids had a common source or that the recrystallized granitoid was derived from partial remelting of the feldspar-phyric granitoid rock.

Proterozoic dykes

Broadly east-northeast-trending mafic and ultramafic dykes (*Edy*) occur throughout KALGOORLIE and YILMIA but are best exposed within the greenstone belts. They are up to 20 km long, generally less than 200 m wide, subvertical, have sharp margins, and are discontinuous with small primary offsets and bifurcations. Concealed basic dykes can be recognized by characteristic subparallel photo lineaments or distinctive, discordant aeromagnetic signatures.

Exceptions to the general east-northeast trend of Yilgarn mafic and ultramafic dykes include dykes in northwest KALGOORLIE and the Saddle Hills. In the Saddle Hills, 2 km southwest of Mount Marion, a 2 km portion of the Celebration Dyke is deflected into the northwesterly greenstone trend and the concealed Parkeston Dyke runs north-northwest from Kalgoorlie to Mount Pleasant across the trends of adjacent greenstones. A dyke of similar orientation was recorded on BOORABBIN 1:250 000 sheet (Hunter, 1989), 9 km north-northeast of Sunday Soak.

Little work has been published on the mafic and ultramafic dykes of KALGOORLIE and YILMIA, but there have been detailed studies of prominent dykes in adjoining areas. Sofoulis (1966) established the term 'Widgiemooltha Dyke Suite' for the generally east–west trending late dykes of the Eastern Goldfields. More recently, the dykes have been called the 'Yilgarn Suite' because of their wide geographic extent (e.g. Parker, 1985; Hallberg, 1987). A description of the post-cratonization dykes of the 'Yilgarn Block' appears in Hallberg (1987).

Samples from the Celebration Dyke which extends into northeast YILMIA and the Jimberlana Dyke to the south 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.

Detailed aeromagnetic data from the Eastern Goldfields reveals that there are both positively and negatively polarized mafic and ultramafic dykes but no cross-cutting relationships between the two types have been observed in the field. West-southwest-trending dykes are positive, whereas the more abundant east–west dykes are negative. Palaeo-magnetic studies (Evans, 1968) suggest that the magnetic orientations are consistent, regardless of the polarity reversal.

On KALGOORLIE and YILMIA, the dykes have sharp contacts, thin (< 5 cm) chilled margins, and coarse-grained gabbroic centres. They are homogeneous and carry only occasional, small felsic xenoliths.

Most dykes are composed of orthopyroxene gabbro, although a few contain olivine gabbro with up to 10% olivine. Large, platy augite crystals are fresh, while smaller grains of orthopyroxene are altered and commonly rimmed by hornblende. Labradorite forms an intercumulus phase (locally sericitized) with accessory opaques and apatite, and plagioclase adjacent to quartz is zoned with andesine cores and oligoclase rims. Quartz (5%) occurs as symplectic or micrographic intergrowths with plagioclase, and mafic minerals are locally altered to amphibole, chlorite, and biotite. This alteration may reflect either late-stage igneous reactions or contamination by assimilated granitoid country rock which was the source of quartz xenocrysts.

McCall and Peers (1971) describe a variety of granophyric enclaves within the mafic and ultramafic dykes which they regard as differentiated portions of the basic magma. However, there is widespread evidence on the BOORABBIN 1:250 000 sheet of thermal metamorphism of granitoids up to 4 m from dyke walls and advanced partial melting within 1 m (Hunter, 1989). Although no examples of back-veining were seen, the conditions were evidently suitable for this to occur. It is probable that the quartzo-feldspathic xenoliths and granophyric enclaves and veinlets are the products of magma contamination by rheomorphic back-veins derived from the granitoid country rock and stoped fragments of the same.

Cainozoic geology

Cainozoic rock and soil form an extensive cover to the Precambrian rocks on the KALGOORLIE and YILMIA sheet areas (Figs 28 and 29). Units were delineated by detailed photo-interpretation, surface morphology, lithological and botanical associations, and representative field inspections. It is evident that some units are diachronous, while others, particularly those that are poorly consolidated, have been or are being reworked. For these reasons the author favours the broader temporal labels, rather than the narrower ones given, for example, by Kriewaldt (1969). A detailed study of the Cainozoic geology of the KALGOORLIE 1:250 000 sheet was presented by Kriewaldt (1974).

General Cainozoic units

Immediately overlying deeply weathered Archaean basement rocks are the remains of a lateritic duricrust

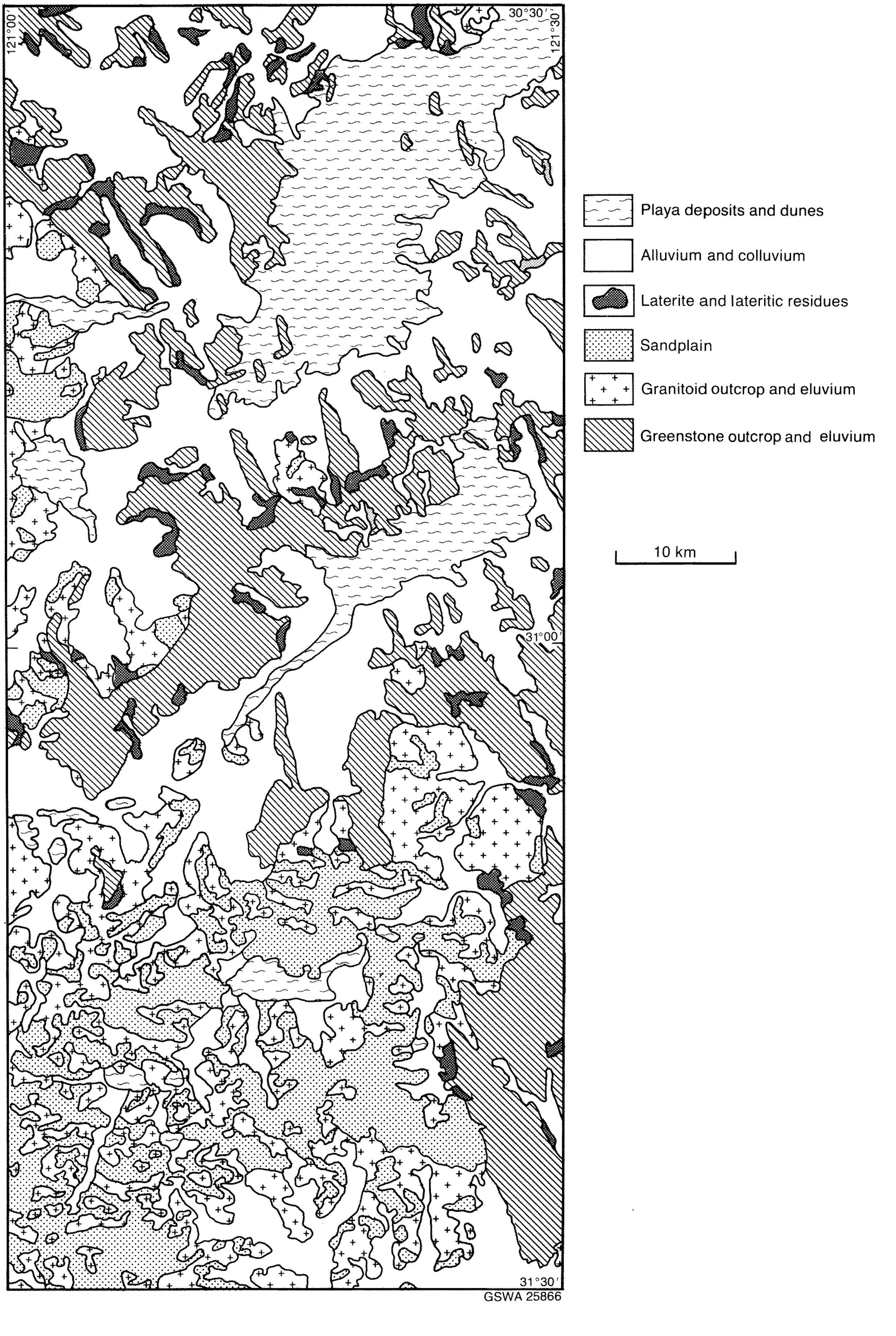

Figure 28. Cainozoic geology of the KALGOORLIE and YILMIA map sheets.

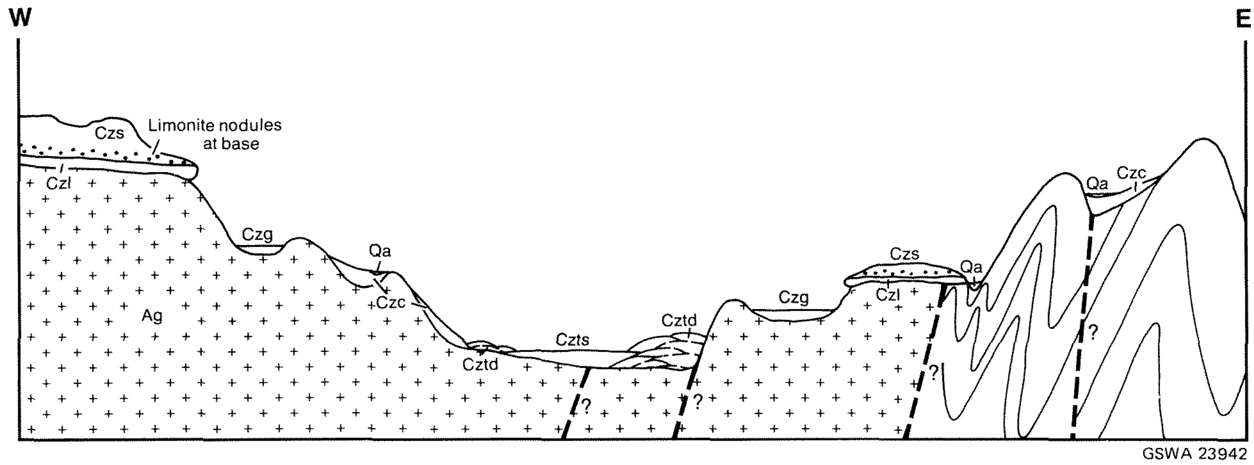

Figure 29. Schematic section showing relationships of Cainozoic units in the KALGOORLIE and YILMIA region.

(*Czl*). Outcrops are confined to the tops of breakaway scarps and their eroded back slopes. The laterite unit comprises: brown to yellow-brown, limonitic pisoliths cemented by subvitreous ferrosiliceous cement; friable rubble associated with the degraded substrate; reworked eluvium, particularly veneers of hematitic granules in dark red gritty soil; and siliceous lateritic material overlying ultramafic rocks. The latter, commonly known as 'cap rock', consists of brown to white varieties of amorphous, cherty silica, such as chalcedony, agate, jasper, and cellular quartz.

Laterite grades upward into a sandplain of yellow to white quartz sand (*Czs*) which is generally mature with traces of iron oxides. Limonite pisoliths are abundant in the sand, particularly near the base above the laterite. Pisoliths with good elliptical or cylindrical shape and hollow interiors have been interpreted as fossil indusia of the curculionid *Leptopius* (Kriewaldt, 1974). The association of sandplain with laterite suggests that it is as a deeply leached fossil soil (Carrol, 1939). However, it is evident that the unit has had an extended history of eolian and fluvial reworking.

Granitic soils (*Czg*) may also be precursors of the sandplain unit. They are pale pink to yellow, coarse, gritty and loamy sands and represent quartzo-feldspathic and fragmental eluvium overlying granitoid rock. They appear to underlie laterite and sandplain, although isolated patches occur on high ground within sandplain. This relationship is interpreted as due to minor reworking of the granitic soils at high points in the palaeotopography under the laterite. Ancient reworking of the lateritic and granitic soil units has produced flat-lying, brown to white, immature sedimentary rocks on low ground. Commonly called 'silcrete' or 'billy', they have a vitreous appearance with mainly medium- to coarse-grained angular quartz clasts and a siliceous or hematitic cement.

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

In the vicinity of playa lakes, two major eolian deposits are recognized according to their degree of consolidation. Stabilized dune deposits (*Cztd*) are white to pale yellow, powdery to gritty, granular soils. They comprise interleaved sand and gypsum forming dunes and hummocky ground along major trunk drainages. These areas are stabilized by halophytes or very open casuarina and eucalypt woodland. The most recent deposits occur on the eastern shore of the current playa lakes. Non-stabilized eolian deposits (included in *Czts*) are white crystalline dunes and banks of gypsum, salt, and sand on the surface of the larger playa lakes. They 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*). The white to grey surface layers are composed mainly of gypsum and salt with a thin, crystalline salt veneer. The surface crust is underlain by 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. These lacustrine deposits (included in *Czts*) are rich in red to grey muds and silt, and are often strongly vegetated around their margins and sometimes across their surfaces.

Quaternary units

Alluvium (*Qa*) is confined to channels or braided river complexes, and comprises unconsolidated or poorly consolidated, immature, poorly sorted sands and gravels. The detritus is locally derived, polymictic, and varicoloured.

Economic geology

Economic production on KALGOORLIE and YILMIA has been sporadic despite the diversity of resources. The following review of economic geology discusses the situation at the time of writing (1987). The gold industry has the longest history with the most interest centred on the Coolgardie and Kalgoorlie areas. Large mining centres in the region have flourished and waned but several are being revived as medium to large tonnage, low-grade opencut operations. Production statistics of gold and other commodities up to December 1987 are given in Tables 6 and 8.

During the 1960s and 1970s the ultramafic rocks of all greenstone belts, concealed and exposed, were thoroughly investigated for their nickel potential. Two nickel mines were established, Nepean and Andrews Shaft (Spargoville), but both are still closed.

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

The courses of palaeorivers in the Eastern Goldfields contain valuable resources of sand, gypsum, and water. Carbonaceous sedimentary rocks have been reported from Coolgardie and exploratory drilling in the palaeodrainage systems south of Kalgoorlie has revealed small quantities of coaliferous sedimentary rocks. There are vast resources of sand and gravel in the region.

Gold

The KALGOORLIE and YILMIA sheets contain two of the most historically significant gold mining centres in Western Australia — Coolgardie and Kalgoorlie. Gold was not reported in this area until 18 September 1892, despite the passage of many exploring expeditions. Bailey and Ford were the first to report gold, and their rich discovery at Coolgardie earned them a Reward Claim and precipitated the first rush to the Eastern Goldfields. As the surface gold became depleted at Coolgardie, a small rush commenced at Mount Youle to the northwest. Three participants in that rush, Hannan, Shea and Flannagan, lingered at Mount Charlotte on 10 June 1893. Within a week Hannan returned to Coolgardie with 100 oz. of gold to register their claim and precipitated the second major rush in the Eastern Goldfields.

Coolgardie has experienced sporadic mining activity in many centres. The more important centres have been described by Gibson (1908), Blatchford (1899, 1913), and McMath et al. (1953). McMath et al. (1953) contains detailed descriptions of most of the mining groups close to Coolgardie. Gibson (1908) has described the geology and detailed the mines of the Kunanalling, Kintore, and 'Bonnie Vale' regions.

The Kalgoorlie–Boulder district has been in continuous production since 1893, although the fortunes of individual mines have fluctuated. Annual production for the district peaked at 39 000 kg in 1903. The importance of the mining centre is reflected in the volumes of literature describing it. A number of significant

Table 6. Gold production statistics, KALGOORLIE and YILMIA sheet areas (to December 1971)

Mining Centre	*Alluvial gold (kg)*	*Dollied gold (kg)*	*Ore treated (t)*	*Gold there from (kg)*	*Silver there from (kg)*
EAST COOLGARDIE MINERAL FIELD					
Binduli	0.08	4.32	9 697.95	89.39	0.05
Boulder	6.15	413.35	102 947 044.16	177 455.18	196 860.41
Hampton Plains	142.70	11.93	621 850.98	4 132.86	187.27
Kalgoorlie	45.74	390.75	17 427 046.28	84 135.07	8 653.87
COOLGARDIE MINERAL FIELD					
Bonnie Vale	1.31	20.27	388 451.57	6 426.14	1.36
Bullabulling	1.17	0.61	6 481.80	75.01	0.01
Burbanks	10.52	27.69	572 326.25	10 349.93	25.49
Coolgardie	71.69	282.70	1 714 794.93	18 177.01	204.13
Hampton Plains	0.15	21.60	314 641.48	4 875.10	929.93
Kintore	4.49	9.01	71 072.92	1 356.63	21.19
Kunanalling	30.57	85.14	157 422.55	3 472.73	2.13
Kundana	-	-	1 516.34	5.04	-
Larkinville	0.71	6.34	3 232.53	144.60	0.47
Logans	0.21	17.50	113 479.77	970.21	1.42
Londonderry	0.52	5.47	39 095.72	775.67	0.71
Mungari	0.18	5.32	5 671.04	39.62	-

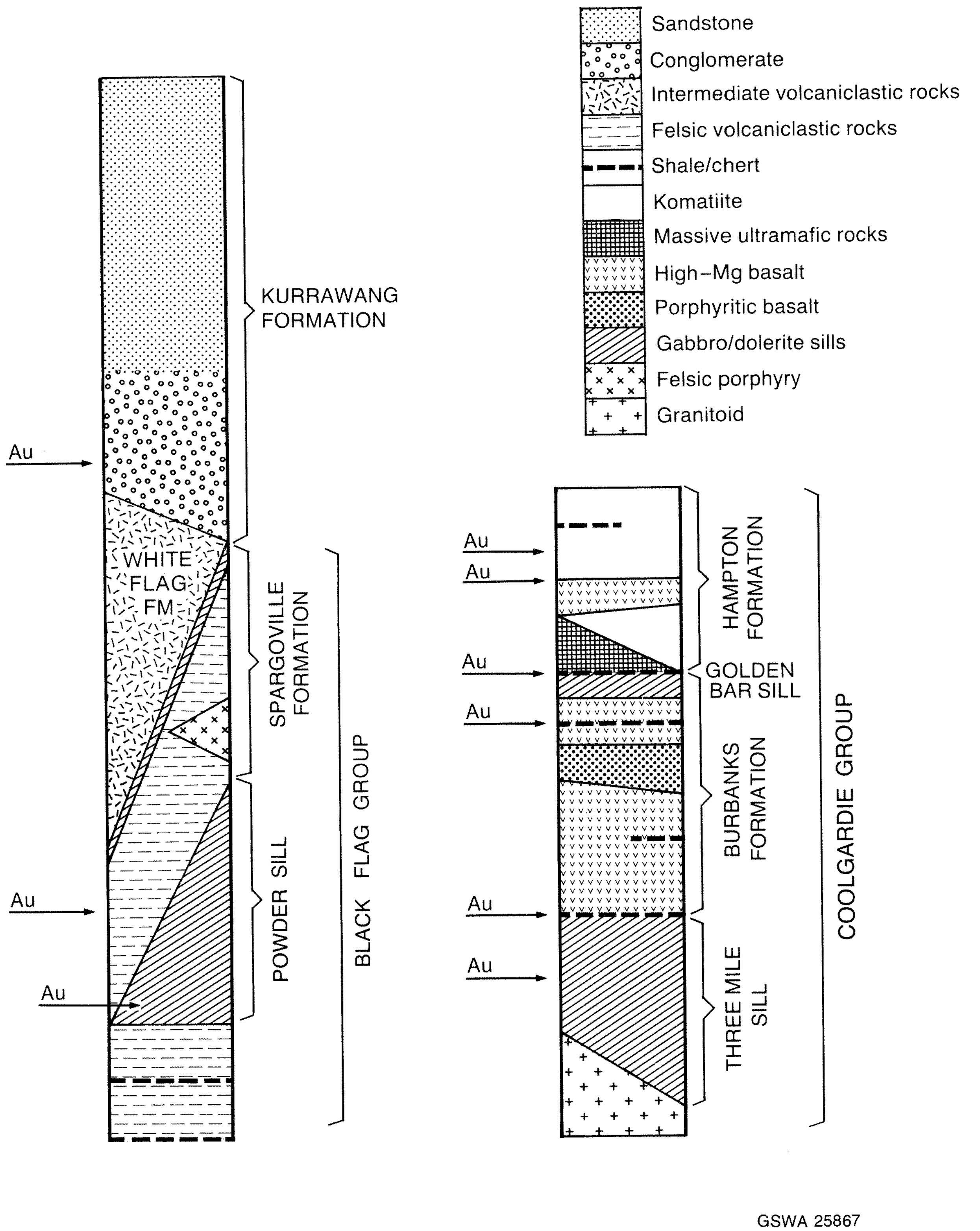

Figure 30. Stratigraphic succession for the KALGOORLIE and YILMIA areas showing principal gold occurrences.

publications have dealt with geology and structure (Larcombe, 1911; Stillwell, 1929; Campbell, 1953; Woodall, 1965), while others contain details of individual deposits (Simpson and Gibson, 1912; Feldtmann and Farquharson, 1913; Feldtmann, 1916; Finucane, 1948; Finucane and Jensen, 1953). Keats (1987) and Swager (1989) provide recent accounts of the geology, mineralization, and mining activity in the Kalgoorlie–Boulder region.

Gold workings are restricted to the greenstone belts and most are located within the mafic–ultramafic portion of the succession, although some deposits on KALGOORLIE occur at the sheared contact between granitoids and greenstones. Alluvial or 'deep-lead' mining has been carried out at a few localities.

Mining and exploration activity has fluctuated but a recent (early- to mid-1980s) resurgence in interest in gold has revived some centres. Current activity is mainly exploiting ground that has had a previous history of mining, although a few new discoveries of concealed deposits have also been made. The Spargos Reward gold mine is notable for both its location within felsic volcaniclastic rock and its relatively recent (1934) discovery. Descriptions of the mineralization are given in statutory reports to the Department of Mines and by Fehlberg and Giles (1984) who interpret this deposit as volcanic exhalative in origin.

There is a correlation between the location of old mines and the intersection of faults or shears with specific horizons in the stratigraphy proposed in this report. The location of the more prominent auriferous horizons is shown in a schematic representation of the stratigraphy (Fig. 30).

At the time of writing (1986–1988), there were extensive gold mining activities on KALGOORLIE and YILMIA; gold mineralization reserves reported then is given in Table 7. In the Kalgoorlie–Boulder district, numerous underground operations are being replaced or supplemented by fewer large-tonnage, low-grade opencut operations. Mining activity is divided between the Kalgoorlie centre towards the northwest and the Boulder centre (The Golden Mile) towards the southeast. The mines of the Kalgoorlie centre are established on essentially new ground, whereas those of the Boulder centre are reviving or extending earlier significant mines. Underground mining is extant at Mount Charlotte, North Kalgurli and Paringa, whereas opencut mining has been introduced to North Kalgurli, Paringa, Great Boulder, Central Kalgoorlie, and Mount Percy.

Mineralization around the Kalgoorlie centre is typified by the Mount Charlotte deposits where gold occurs in the wall-rock alteration selvedges to a sheeted quartz-vein system (Keats, 1987). The quartz stockwork occurs within an iron-rich, granophyric zone of a differentiated gabbro sill (Golden Mile Dolerite). The veining is confined by, but closely associated with, north-striking wrench faults. To the east of Mount Charlotte, discontinuous lodes occur in a number of structural environments and within a range of host rocks that span the Kalgoorlie stratigraphy. In the north, mineralization occurs in quartz porphyries within ultramafic rock or is associated with quartz veining in basalt, slate, and dolerite.

Table 7. Reported gold mineralization reserves, KALGOORLIE and YILMIA sheet areas

Mine	*Reserves (a)*				*Date reported*
Bayleys	0.400 Mt	@	15.00 g/t	(I)	21/07/87
Blue Funnel	0.470 Mt	@	3.24 g/t	(D)	01/02/88
Brilliant	0.100 Mt	@	2.10 g/t	(D)	05/02/88
Burbanks	0.061 Mt	@	6.00 g/t	(P)	05/11/87
Grosmont	0.695 Mt	@	4.50 g/t	(D)	25/11/87
	0.890 Mt	@	4.50 g/t	(I)	25/11/87
Kunanalling	2.130 Mt	@	1.49 g/t	(D)	23/11/87
(London)	1.065 Mt	@	1.49 g/t	(I)	23/11/87
Kunanalling	0.320 Mt	@	3.20 g/t	(D)	00/06/87
(Premier)	0.520 Mt	@	3.20 g/t	(I)	00/06/87
Mount Pleasant	3.000 Mt	@	5.50 g/t	(D)	02/02/88
Tindals	0.502 Mt	@	3.48 g/t	(D)	05/03/87

(a) (I) Inferred (D) Demonstrated (P) Probable

Mineralization in the Boulder centre occurs in two lode systems which are separated by a major strike-slip fault (Golden Mile Fault). In the eastern lode system, mineralization occurs mainly in the Golden Mile Dolerite but continues at depth and northward into adjacent basalts (Paringa Basalt). Mineralization in the western lode system is confined to the Golden Mile Dolerite but no lithostratigraphic base has yet been defined. Economic mineralization in the Boulder centre is confined structurally by two major oblique faults, the Adelaide Fault to the southeast and the Golden Pike Fault to the northwest.

Beyond Kalgoorlie and Boulder, particularly around Coolgardie, medium- to low- tonnage, low-grade, opencut operations are abundant. Underground operations are scarce and restricted to deeper, larger operations (e.g. Mount Pleasant) or to small, ephemeral workings of prospectors.

In the Black Flag region, mineralization commonly occurs in quartzose shear zones within porphyritic basalts and several deposits have proven medium- to high-grade reserves. The Black Flag Fault has been a regional controlling influence on gold mineralization.

Just west of Mount Pleasant there is substantial mineralization of some horizons in a layered gabbro sill. The zones of gold mineralization have a close spatial relationship with the Black Flag Fault but are confined to shears oriented west and west-southwest. The two main zones being exploited, the 'Golden Kilometre' and adjacent 'Southern Shoot', had combined reserves of

3.0 Mt at 5.5 g/t in 1988. At the Lady Bountiful mine, 2.5 km along strike to the northwest, mineralization is within the same layered gabbro, where it has been intruded by the concealed Liberty Granodiorite (granitoid name formalized by Witt, 1990). The gold occurs mainly in veins in east–west sinistral shears but is also found in narrow, northeast-trending quartz veinlets. Gold mineralization grades are erratic but there may be more than 1 Mt at 4 g/t (1987).

At Blue Funnel, there is a small, but rich, deposit within the concealed Mungari Shear Zone*. This structure has juxtaposed ultramafic–mafic rocks with conglomerates of the Kurrawang Formation. Gold mineralization occurs in shears and quartz-filled gashes en-echelon to the shear zone. Although 1987 reserves of 0.2 Mt at 6.5 g/t have been published, some 'best drilling intercepts' have spectacular values; 1988 reserves are shown in Table 7.

Up to 1988, exploration in the Kintore–Kunanalling area had failed to reveal any large deposits, although encouraging results had been obtained from a sheared granitoid near the London mine and various prospects along the Kunanalling Shear Zone to the southeast.

There has been a lot of recent exploration activity in the Coolgardie district, particularly since the highly publicized reopening of the McPhersons Reward mine. Mineralization at the mine occurs within a quartz porphyry sill intruded between komatiite above and basalt below. Auriferous, gash quartz veins have a northwest orientation, parallel to local cross faults. Reserves have not been published but parcels of very rich ore are treated from time to time.

Oxidized ore at the Brilliant opencut has recently been mined out but proven reserves of sulfide ore remain undisturbed. The mineralized horizons are felsic porphyries at the boundary between komatiite schists and a thin, high-Mg basalt horizon. The felsic rocks are enigmatic but appear to be conformable and poly-deformed with the wallrocks. Auriferous quartz veins are associated with northeast cross faults. A similar style of mineralization occurs at Tindals but folding and shearing is more complex and pervasive. Reserves for 1987 are shown in Table 7.

The Barbara and Surprise group of mines occur within komatiite, close to a narrow basaltic horizon. The ultramafic rocks are intruded by subconformable sills of quartz–feldpar porphyry and hornblende–plagioclase porphyry, and mineralization occurs in narrow, steeply dipping shear zones near the contact between the porphyries and komatiite. Gold is concentrated mainly within ultramafic rocks but some resides within the porphyries. Historically, gold production has been of low tonnage but the grade has been high.

Refurbishment of shafts in the Bayleys group is continuing, following encouraging drilling results. Mineralization occurs in interflow sedimentary rocks and porphyries within a komatiite unit and is controlled by shears.

Mineralization in the Grosmont mining area is confined to northeast-trending shear zones mainly within komatiite but also close to the contact with the adjacent basalt. Gold occurs in quartz reefs and as stringer lodes in the schistose host. There is another shear set orthogonal to the gold-bearing shears but, while both have been intruded by pegmatite, only one carries gold. In 1987, opencut mining was in progress at Grosmont and previously stockpiled ore, with an average grade of just under 3 g /t, was being treated.

At Burbanks, the main gold occurrences are in lenticular quartz reefs within basalts, while lesser concentrations occur in east–west trending quartz veins. The northeasterly trend of workings parallels the locus of the highly sheared axial plane of a syncline which has been transected by faults trending west to northwest. While one opencut mine west of Burbanks town dam operated periodically from 1984 to 1987, extensive exploration in the region concentrated on extensions of the mineralized Burbanks shear.

To the southeast at Spargos Reward, free gold occurs within biotite-rich pelites and psammites. The ore body is composed of a series of stacked, plunging lenses which are conformable with bedding. Mineralization is not associated with quartz veining, although very high values occur at intersections of quartz leaders and the ore body. Also, despite local spatial association between lodes and drag folds, there does not appear to be a structural control on mineralization. The mine underwent an extensive dewatering, refurbishing and drilling program in the mid-1980s, and reserves were reported to be 100 000 t at 7.6 g/t down to 90 m (1985).

Nickel

Economic and subeconomic nickel deposits occur at the base of komatiite flows west of Londonderry, at Nepean, and south of Spargoville.

Nepean

The Nepean deposit was discovered in March 1968 through the drilling of induced polarization anomalies associated with ultramafic lavas and sulfidic sedimentary rocks (Sheppy and Rowe, 1975). The first parcel of ore was taken to Kambalda for treatment in January 1970 and subsequent annual production averaged a little over 2 000 t. However, the complexities in the structure, thickness, and grade of the ore bodies caused a sharp decline in economic reserves from 1979 onwards. The Nepean mine ceased production in May 1987 when economic reserves were mined out; the overall nickel production was 34 830.35 t.

A concise account of the Nepean deposit by Marston (1984) includes the production history and details of the mineralogies of the host rocks and ore bodies. The local stratigraphy is equivalent to that to the north in the

* Now renamed to the Zuleika Shear Zone.

Gibraltar–Burbanks region and forms a synclinorium which has been intensely modified by strike faulting and shearing. Ore bodies are located mainly at ?lower contacts between komatiites and basalts, although there is one which occurs partly within a basalt. They generally consist of matrix ore, although some massive and vein types do occur locally. The opaque mineralogy of unoxidized ore comprises mainly pentlandite–pyrrhotite and chalcopyrite with or without pyrite, chromite, and magnetite. It is apparent from studies (Barret et al., 1976, 1977) of the textures and chemistry of the ore that high-grade regional metamorphism and subsequent retrograde effects have greatly modified original magmatic features.

Andrews Shaft

The deposits south of Spargoville were discovered in 1966-67 as a result of a combined program of geological mapping, airborne and ground magnetic surveys, and soil geochemistry surveys (Andrews, 1975). The initial indications of mineralization were nickel and copper anomalies defined by the soil sampling. Production did not commence until March 1975 because of difficulties experienced during shaft sinking and it was 1978 before an operating profit was achieved. 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).

A detailed account of the Spargoville nickel deposits, including production statistics and ore mineralogy, is given by Marston (1984). The mine is located in a narrow belt of mafic and ultramafic volcanic and intrusive rocks which is interpreted as an anticline modified and repeated by intense strike faulting and shearing. Mineralization occurs in the basal zone of a komatiite overlying basalt and is controlled by embayments or depressions in the contact surface (Andrews, 1975). It occurs in ribbon-like to lens-shaped concentrations of mixed disseminated, matrix, and massive sulfides which have strike lengths in the range of 50 to 300 m and an average thickness of about 5 m. The primary sulfide minerals are pyrrhotite and with or without pyrite, chalcopyrite, gersdorffite, and niccolite (Hancock et al., 1971).

Other prospects

There are three deposits to the north and west of the Londonderry gold mine which 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. The northernmost deposit, Miriam, has been described by Hallberg et al. (1973) and Gemuts (1975), and has an inferred resource of 227 000 t averaging 1.7% Ni (3 859 t contained Ni). The primary sulfide assemblage of pentlandite and pyrrhotite with or without chalcopyrite and pyrite occurs in disseminated zones and minor massive zones from 1 to 10 m wide. To the south, the Bouchers and North Bouchers prospects have similar characteristics but are generally smaller (Marston, 1984).

Three other nickel prospects within a four kilometre radius of Andrews Shaft have been evaluated and described by Andrews (1975). The stratigraphic location and mineralogy of these deposits is similar to that at Andrews Shaft; demonstrated resources were noted by Marston (1984): 1A, 365 000 t (2.53% Ni); 2 (5B), 119 520 t (2.32% Ni); and 5A, 43 600 t (4.74% Ni) (Marston, 1984).

Pegmatite and related minerals

Feldspar

The only major producer of feldspar is the Londonderry group of quarries in which a number of thick sheets and dykes of compositionally zoned pegmatite cut an upright, isoclinally folded sequence of gabbro, basalt, and komatiite. A description and maps of the deposits appears in McMath et al. (1953).

The pegmatite was first quarried by E. Scahill for microcline in 1932 but minor amounts of beryl and columbite were also produced (Forman, 1937b). War-time interest in petalite prompted a study of this and nearby pegmatite occurrences by Ellis (1944a,b), and petalite was subsequently mined for lithium. There is a diverse assemblage of minor and exotic minerals in the pegmatite. These are described by Le Mesurier (1944), Simpson (1948) and Hill (1976), and in academic studies by Martin (1965) and Haynes (1966). Recent production

Table 8. Production statistics of pegmatite minerals, KALGOORLIE and YILMIA sheet areas (to December 1987)

Mining Centre	*Feldspar*	*Quartz*	*Tantalite–Columbite*	*Lepidolite*	*Petalite*	*Beryl*
			(t)			
COOLGARDIE MINERAL FIELD						
Burbanks	1.00	-	-	-	-	-
Coolgardie	-	998.00	-	8.48	-	-
Londonderry	74.31	242.00	0.88	2.48	3 041.97	255.05

of the pegmatite minerals has been erratic and the Londonderry quarries are currently idle. Production statistics of pegmatite minerals up to 1987 are shown in Table 8.

Spodumene

In the Saddle Hills south of Mount Marion, there are a number of flat-lying pegmatite bodies which intrude basalt and gabbro. Each pegmatite shows textural and compositional zoning parallel to and mineral growth perpendicular to its walls (Ross, 1964). The main minerals present are quartz, microcline and plagioclase, while spodumene comprises 25–50% of the rock, depending on locality. A list of the other minerals present is given by Ross (1964). Spodumene is present as pale green prisms up to 1 m in length which assay 6.08% Li (Tomich, 1956). There has been no production from this deposit but there are indicated reserves of 3 Mt at 1% Li oxide.

Other minerals

Small quantities of tantalite–columbite have been recovered from pegmatites at Londonderry, Tantalite Hill, Mount Marion and south of Spargoville. The Spargoville 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%), and SnO_2 (0.40%).

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

Cassiterite and beryl have been won from several pegmatites but not in large amounts. The latter forms large crystals at Londonderry and Spargoville.

Other commodities

Sand and gypsum

Thick deposits of yellow to white quartz sand (*Czs*) occur on the sandplains. Lower levels of the unit contain limonite nodules but the upper levels, particularly where recent reworking has occurred, have good quality sands suitable for building and fluxing. Sand also occurs in thick eolian 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 gypsum rich but this resource has yet to be exploited. These deposits of sand and gypsum are far from bulk-handling facilities and the consequent high costs of road/track haulage renders many of them uneconomic.

Coal and oil shale

Studies of the palaeodrainage systems in parts of Western Australia (Bunting et al., 1974; van de Graaf et al., 1977) have revealed the potential for coal and oil shale in the Cainozoic sediments which fill the playas and associated trunk drainages. Exploration in the WIDGIEMOOLTHA and NORSEMAN 1:250 000 sheet areas has been encouraging but no economic deposits have been found (Griffin, 1989). A portion of the Lefroy palaeoriver was drilled in a few places in the southeastern corner of BOORABBIN 1:250 000 sheet area (Hunter, 1989) but basement was encountered at shallow depths. Minor evidence of marine incursion in this area includes sparse occurrences of sponge spicules and glauconite, and the 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

The occurrence of fuchsite and sericite in massive to flaggy rocks within a silicified shear zone between Spargoville and Larkinville has provided an interesting decorative stone (prase). 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. Silicification of a grey shale unit underlying komatiite at Three Mile Hill has produced small quantities of precious opal.

Well formed examples of exotic minerals (e.g. beryl) are common in the diverse pegmatites of KALGOORLIE and YILMIA.

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Appendix

A gazetteer of localites referred to in the text

Locality	*AMG Reference (a)*	
	E	*N*
Andrews Shaft	356800	6529400
Bakers Find	327650	6567100
Bali	311500	6571300
Barbara mine/group	332500	6573100
Bayleys mine/group	326200	6574900
Binduli Mining Centre	347150	6589200
Black Flag Homestead	330300	6619300
Black Flag Lake	336500	6618500
Black Flag Mining Centre	330300	6619300
Blue Bell mine	316850	6602700
Blue Dam	342000	6581800
Blue Funnel mine	320000	6615000
Bonnie Vale mine/Mining Centre	323500	6584100
Boorabbin Rock (b)	241500	6544500
Bouchers prospect	317700	6559600
Boulder town/Mining Centre	355500	6593000
Brilliant mine/opencut	326300	6572150
Broad Dam	318200	6617000
Brown Lake	336500	6576000
Bullabulling mine/Mining Centre (b)	296300	6567000
Burbanks mine/Mining Centre	322100	6565900
Burbanks Siding	322500	6565000
Burbanks Town Dam	322000	6565400
Burra Rock	328500	6525300
Calooli	316500	6571500
Cane Grass Swamp	326000	6591000
Cattle Swamp	328000	6592000
Celebration Dyke	356000	6564700
Central Kalgoorlie mine	353550	6597400
Change Creek	340500	6565500
Comet Hill	315800	6565950
Connolly Siding	334000	6542100
Coolgardie town/Mining Centre	324600	6573800
Coondarrie (b)	302000	6574800
Crown Dam	329000	6615450

(a) Localities are specified by the Australian Map Grid (AMG) standard reference system. The first group of numbers (eastings) and the second group (northings) together define the locality position, on the map sheets discussed, to within 100 metres.

(b) Site on adjacent map sheet.

Locality	AMG Reference (a)	
	E	N
Depot Hill	351600	6551250
Depot Rock	350400	6551000
Diamond Rock (b)	346800	6502500
Drydens mine	330400	6583100
Durgulyie Rock	322600	6534500
Eight Mile Rock Dam	308700	6590900
Ellen Dam	349600	6571800
Enclosure Dam	325250	6508650
Gibraltar (b)	305750	6563750
Gibson–Honman Rock	349750	6586500
Gimlet South mine	313500	6637900
Golden Kilometre mine	330700	6621900
Goongarrie (b)	322800	6674800
Grants Patch Mining Centre (b)	319000	6630000
Great Boulder mine (b)	356800	6593250
Grosmont mine	314100	6562300
Gunga mine	329700	6578900
Hampton	328500	6572500
Hampton Plains Station	334200	6569200
Hampton Locality 59 (SE cnr)	331400	6553400
Higginsville (b)	377000	6487000
Holmans mine	354950	6533050
Horans Dams/Big Dam	347450	6606550
Horse Rocks	347650	6555450
Jaurdi Hill (b)	302200	6604000
Kalgoorlie town/Mining Centre	353600	6597500
Kambalda (b)	373000	6548000
Kangaroo Hills	316000	6562000
Kanowna town/Mining Centre(b)	336600	6613000
Kanowna Homestead	347600	6624500
Karramindie (Soak)	344450	6566350
Kintore mine/Mining Centre	310100	6612850
Kunanalling mine/Mining Centre	314700	6603700
Kundana mine/Mining Centre	330000	6601700
Kurrawang Mission	340200	6588000
Kurrawang Lake	330700	6592800
Lady Bountiful mine	327650	6623900
Lake Douglas	345900	6586200
Larkinville mine/Mining Centre	357200	6520800
Last Chance mine	310300	6609900
Laurie Dam	320800	6623300
Logans Find	349050	6531050

Locality	AMG Reference (a)	
	E	N
Logans Mining Centre	349050	6531050
London mine	311500	6608500
Londonderry gold mine	319400	6561200
Londonderry pegmatite mine	316500	6555900
Londonderry Mining Centre	319400	6561200
Lord Bob mine	318950	6565550
McPhersons Reward mine	327900	6569300
Miriam mine	318850	6562900
Monument Dam	326500	6600550
Mount Burges	317800	6586900
Mount Burges Homestead	319800	6585400
Mount Charlotte mine	354400	6597500
Mount Eddy mine	345850	6622500
Mount Herbert	350500	6563900
Mount Marion	351900	6563100
Mount Percy mine	353750	6599050
Mount Pleasant	332370	6621900
Mount Pleasant copper mine	334150	6624300
Mount Robinson	335500	6577750
Mungari mine	336600	6584500
Mungari Homestead	334700	6584500
Mungari Mining Centre	336600	6584500
Nepean mine	317300	6550250
Nickel smelter	355000	6583300
North Bouchers prospect	318750	6561650
North Dam	351800	6533600
North Kalgurli mine	356300	6594600
Northlander mine	320550	6594300
Ora Banda Mining Centre	314500	6638100
Paringa mine	356400	6594800
Pennisula	389100	6463900
Perron Dam	336100	6578950
Powder Dam	321250	6609500
Premier mine	315000	6604500
Quairnie Rock	317000	6539400
Queen Victoria Rock (b)	302500	6535750
Red Lake	342000	6579300
Reid Dam	355600	6530000
Ridge mine	301900	6613500
Saddle Hills	352000	6562500
Seven Mile Hill	345200	6587900
Southern Shoot mine	330700	6621900

Locality	*AMG Reference (a)*	
	E	*N*
Spargos Reward mine	354200	6543100
Spargoville	354300	6543300
Spargoville Reservoir	354550	6543900
Star of Fremantle mine	319100	6600200
Stennet Rocks (b)	365000	6392300
Surprise mine/group	334000	6572800
Survey Dam	356250	6561000
Sydney Mint mine	310600	6608200
Tantalite Hill mine	316250	6558000
Telegraph Dam	315900	6609300
Ten Mile Dam	355700	6513050
Ten Mile Rocks	338600	6517500
The Gorge	327250	6572800
Three Mile Hill	327500	6577100
Thursday Rock (b)	227500	6508000
Tindals mine	325800	6570200
Town Dam	331250	6617350
Twenty Grand mine	353900	6531650
Twenty Seven Dam	329500	6613500
Two Dams	332950	6578500
West Canegrass Dam	311600	6586400
Wheeler Rock (b)	300050	6435000
White Flag Lake	333300	6609500
Widgiemooltha (b)	361500	6514800
Woolgangie Soak (b)	326650	6549500
Yilmia Siding	330750	6545000
Yilmia Hill (b)	359300	6544800
Zuleika	313800	6620650

(a) Localities are specified by the Australian Map Grid (AMG) standard reference system. The first group of numbers (eastings) and the second group (northings) together define the locality position, on the map sheets discussed, to within 100 metres.

(b) Site on adjacent map sheet.

Locality index

The suffix F or T indicates that the reference is to a Figure or Table appearing on that page.

12809/8/93-600-L/6147

KALGOORLIE

GEOLOGICAL SURVEY OF WESTERN AUSTRALIA

QUATERNARY

- Qa — Alluvium; clay, silt, sand and gravel in channels

CAINOZOIC

- Czts — Evaporite interbedded with clay and sand in playas
- Cztd — Sand silt and gypsum in stablized dunes adjacent to playas
- Czc — Colluvium; gravel, sand and loam as sheetwash and talus
- Czg — Quartzo-feldspathic sand over granitoid rock
- Czs — Sandplain; yellow sand with limonitic pisoliths near base
- Czl — Laterite and reworked products

PROTEROZOIC

- Pdy — Mafic and ultramafic dykes

ARCHAEAN

- Ag — Granitoid rock
  - Agc — CALOOLI MONZOGRANITE: medium biotite monzogranite
  - Agmu — MUNGARI MONZOGRANITE: medium biotite — muscovite monzogranite
  - Agbl — BALI MONZOGRANITE: coarse porphyritic biotite monzogranite
  - Agnm — NINE MILE MONZOGRANITE: coarse porphyritic biotite monzogranite
  - Agkn — KINTORE TONALITE: medium biotite tonalite
- Asf — Metamorphosed felsic volcaniclastic rock, mainly sedimentary with tuff
- Ash — Metamorphosed shale and chert
- Ask — KURRAWANG BEDS: conglomerate and sandy conglomerate; boundaries of magnetic banded iron-formation pebble horizon indicated
- Asa — KURRAWANG BEDS: sandstone and pebbly sandstone
- Aiv — Metamorphosed intermediate volcaniclastic rock, tuff to tuff-breccia
- Af — Metamorphosed felsic volcanic and volcaniclastic rock
  - Afp — Metamorphosed intrusive dacite and rhyodacite porphyry
  - Aft — Metamorphosed dacite and rhyodacite tuff-breccia and tuff
  - Afv — Metamorphosed felsic volcaniclastic rock; mainly tuff and lapilli-tuff with minor sedimentary rock
- Afs — Schist derived from felsic volcanic, sub-volcanic and volcaniclastic rock
  - Afsa — Pelitic schist bearing andalusite megacrysts
- Ao — Metamorphosed mafic and ultramafic intrusive rocks
  - Aod — Metamorphosed dolerite
  - Aog — Metamorphosed gabbro
  - Aol — Leuco-granodiorite to tonalite with acicular megacrysts and micrographic texture
- Ab — Metamorphosed mafic extrusive rocks
  - Aba — Metamorphosed mafic agglomerate
  - Abm — Metamorphosed high-Mg basalt
  - Abp — Metamorphosed porphyritic basalt and dolerite
- Au — Ultramafic schist
  - Aku — Metamorphosed komatiite flows, with spinifex texture
  - Akp — Pillowed or massive ultramafic rock

Geological boundary, with breakaway
Fault, inferred or concealed
Shear zone
Folds, showing plunge
- anticline, approx
- syncline, approx
- overturned anticline, approx
- minor anticline
- minor syncline
- minor fold

Bedding
- inclined
- vertical

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

Cleavage
- inclined
- vertical

Lineation
Metamorphic foliation
- inclined, with lineation
- vertical

Compositional layering, inclined
Joint
- inclined
- vertical

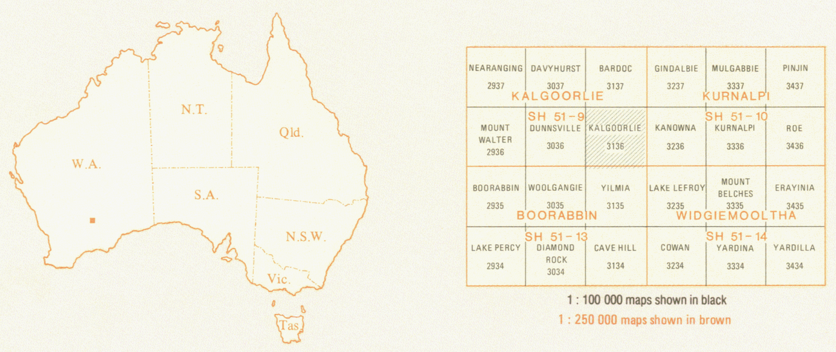
Air photo lineament
- concealed mafic dyke
- lithological trend
- probably reflecting underlying fault

Foliation
Sand dune
Breakaway
Contour line, 20 metre interval
Mineral exploration drill hole
Down hole stratigraphy

Mineral field boundary
Mineral field district boundary
Highway with national route marker
Formed road
Track
Fence
Powerline
Railway, with siding — Hampton
Railway, abandoned
Old woodline formation
Population centre
- pop. over 10,000 — KALGOORLIE
- pop. less than 1,000 — Coolgardie

Homestead — Black Flag
Locality — Binduli
Horizontal control; major, minor
Transmitter or repeater site, building
Watercourse, ephemeral
Pipeline — P
Dam — D
Well — W
Abandoned — (abd)
Mining locality — BONNIE VALE
Mine or open cut (gold unless otherwise indicated) — Bayleys Reward
Potential mine
Alluvial or deep lead
Mine area or tailings
Battery, battery abandoned
Mineral occurrence
- Copper — Cu
- Gold — Au
- Magnesite — Ms
- Opal — Op

Pit
- Building stone — Bs
- Gravel — Gr
- Rock — Rc
- Sand — Sd



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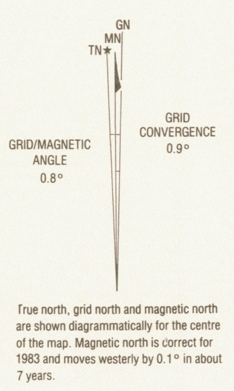
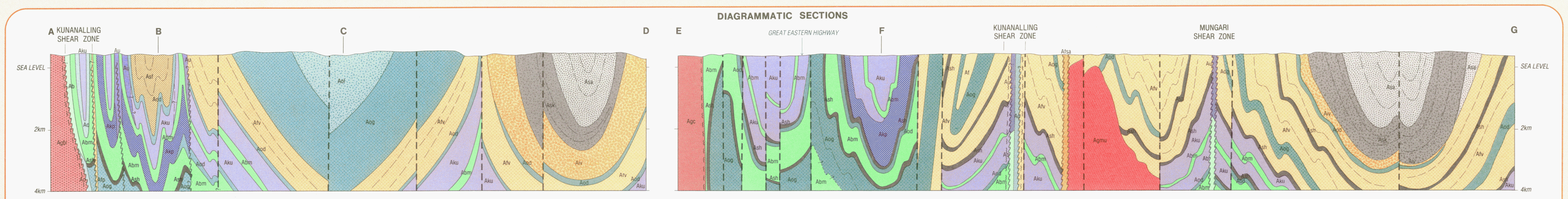


True north, grid north and magnetic north are shown diagrammatically for the centre of the map. Magnetic north is correct for 1983 and moves westerly by 0.1° in about 7 years.

DIAGRAMMATIC SECTIONS



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D.R. KELLY, DIRECTOR GENERAL OF MINES

P.E. PLAYFORD
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OF WESTERN AUSTRALIA

SCALE 1:100 000

UNIVERSAL TRANSVERSE MERCATOR PROJECTION
Grid lines indicate 1000 metre interval of the Australian Map Grid Zone 51

Geology by: W.M. Hunter 1985
Cartography by the Surveys and Mapping Division, Department of Mines, Western Australia.
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KALGOORLIE

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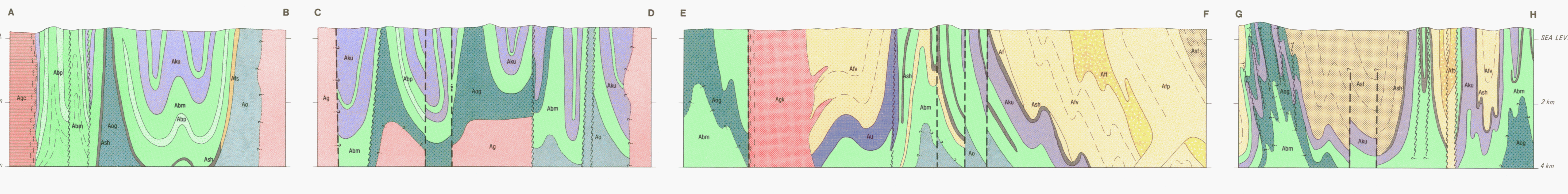
SHEET 3135

DIAGRAMMATIC SECTIONS



CAINOZOIC

QUATERNARY

Qa — Alluvium; clay, silt, sand and gravel in channels

Czts — Evaporite interbedded with clay and sand in playas
Cztd — Sand silt and gypsum in stabilized dunes adjacent to playas

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Czs — Sandplain; yellow sand with limonitic pisoliths near base
Czl — Laterite and reworked products

PROTEROZOIC

Ƥdy — Mafic and ultramafic dykes; Ƥdyc — Celebration Dyke, Ƥdyr — Randalls Dyke

ARCHAEAN

Ag — Granitoid rock
Agc — **CALOOLI MONZOGRANITE**: medium biotite monzogranite
Agd — **DEPOT GRANODIORITE**: hornblende granodiorite and tonalite with scattered microcline phenocrysts
Agk — **KARRAMINDIE MONZOGRANITE**: recrystallized biotite and monzogranite
Agph — **BURRA MONZOGRANITE**: coarse porphyritic monzogranite
Agbl — **BALI MONZOGRANITE**: coarse porphyritic biotite monzogranite
Agr — **WOOLGANGIE MONZOGRANITE**: recrystallized monzogranite and granodiorite
Agp — Pegmatite

An — Banded granitoid gneiss
Anst — Granodiorite and tonalite gneiss with streaky augen of quartz and granular feldspar

Asf — Metamorphosed felsic volcaniclastic rock, mainly sedimentary with tuff
Ash — Metamorphosed shale and chert

Af — Metamorphosed felsic volcanic and volcaniclastic rock
Afp — Metamorphosed intrusive dacite and rhyodacite porphyry
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Au — Ultramafic schist
Aku — Metamorphosed komatiite flows with spinifex texture

Geological boundary
Fault, inferred or concealed
Shear zone
Fold, showing plunge
- anticline, approximate
- syncline, approximate
- minor fold, with plunge

Bedding
- inclined
- vertical

Younging indicator
- sedimentary
- graded bedding
- lava pillows
- differentiated intrusions

Cleavage
- inclined
- vertical

Lineation
Metamorphic foliation
- inclined, with lineation
- vertical

Compositional layering
- inclined
- vertical

Joint
- inclined
- vertical

Air photo lineament
- concealed mafic dyke
- lithological structural trend

Foliation

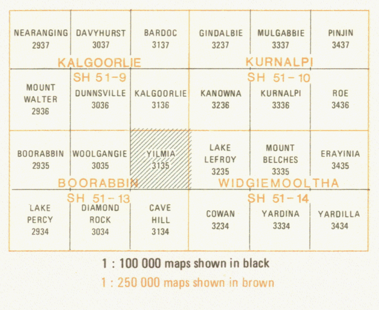
Highway with national route marker
Formed road
Track
Railway, abandoned
Old woodline formation
Fence
Locality — Spargoville
Horizontal control; major, minor

Sand dune
Breakaway
Contour line, 20 metre interval

Watercourse, ephemeral
Pipeline
Dam

Mining locality — BURBANKS
Mine or open cut (gold unless otherwise indicated) — Spargos Reward
Mineral exploration drill hole
Downhole stratigraphy — Abm
Mineral occurrence
- Gold — Au
- Nickel — Ni
- Pegmatite — Pg

Pit
- Gravel — Gr
- Sand — Sd



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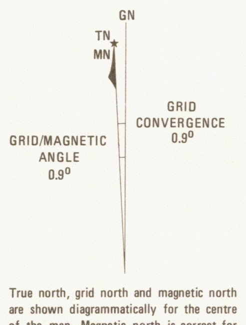

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