GEOLOGICAL SURVEY OF WESTERN AUSTRALIA

1:250 000 GEOLOGICAL SERIES—EXPLANATORY NOTES

WIDGIEMOOLTHA

WESTERN AUSTRALIA

SECOND EDITION

SHEET SH 51-14 INTERNATIONAL INDEX

WESTERN AUSTRALIA
INDEX TO GEOLOGICAL MAPS
SCALE 1:250 000

SECOND EDITION

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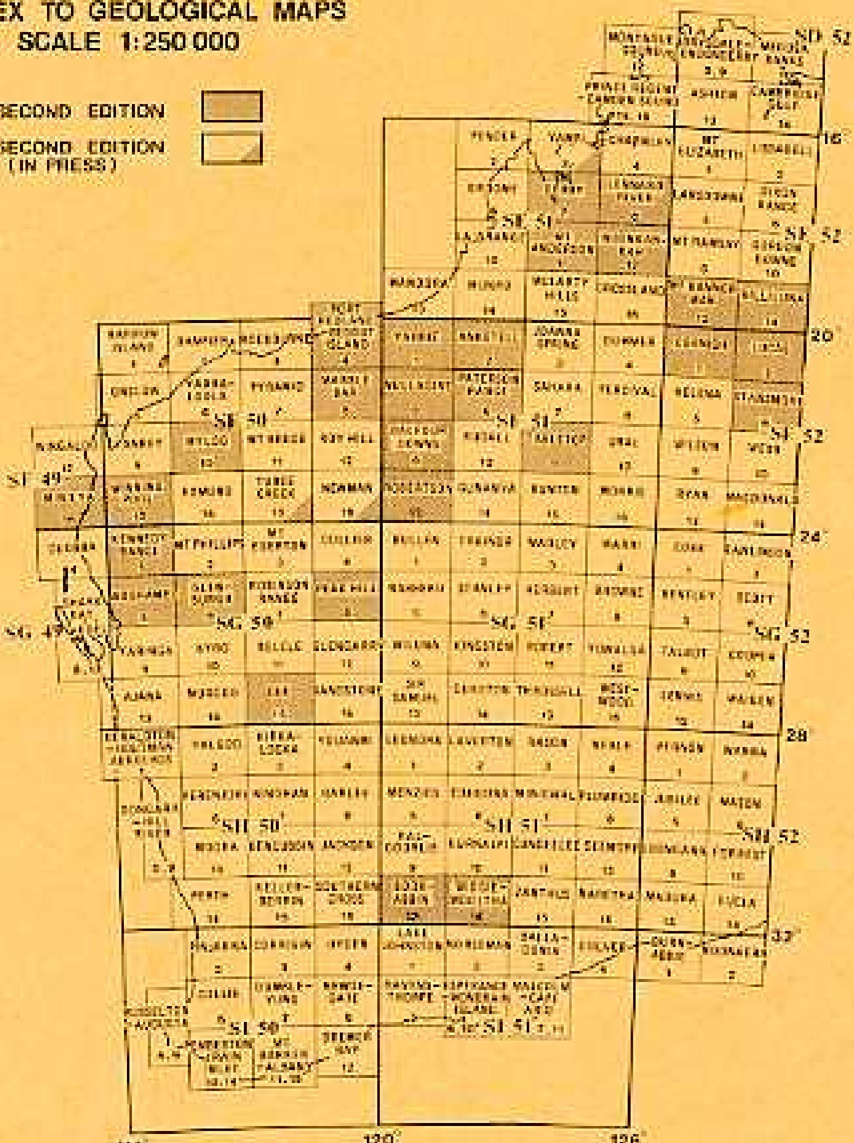

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BY

T. J. GRIFFIN

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(Second Edition)

by T.J. Griffin

INTRODUCTION

The WIDGIEMOOLTHA* 1:250 000 sheet (SH 51-14 of the International Series) is bounded by latitudes 31°00′ and 32°00′S and longitudes 121°30′ and 123°00′E. It takes its name from the small township of Widgiemooltha, located near the centre of the western margin of the sheet on the Coolgardie–Norseman Highway.

Mining is the major activity of the region and there is a large permanent community at Kambalda (population 3519, in 1986); there is direct access by road to the major communities at Kalgoorlie, Coolgardie and Norseman. Grazing is carried out over most of the northwestern two-thirds of WIDGIEMOOLTHA, and the grassed hills of the Fraser Range in the southeastern corner.

PHYSIOGRAPHY

The generally dry, saline, lake systems of Lake Lefroy and Lake Cowan (about 280 m and 260 m above sea level, respectively) dominate the western half of WIDG-IEMOOLTHA (Fig. 1). The highest hills are Yilmia Hill (446 m) and a peak in the Fraser Range (527 m). Most hills are on the western side of the sheet, and the best exposures occur where steep slopes are close to lakes. Nevertheless, steep slopes and gullies are generally scree covered and cannot be relied on to provide good outcrop alone.

Dunes of quartz sand and gypsum are abundant on the eastern and southern sides of lakes. Further away, the land surface is flat and covered by sandy soil with various amounts of kankar (carbonate nodules) or ironstone (hematite and maghemite) pisoliths.

Isolated outcrops of flat-lying Tertiary sedimentary rocks, laterite, silcrete and calcrete surfaces, form small plateaus at all topographic levels, particularly adjacent to drainage systems and in breakaways.

* Sheet names are printed in full capitals to distinguish them from similar place names.

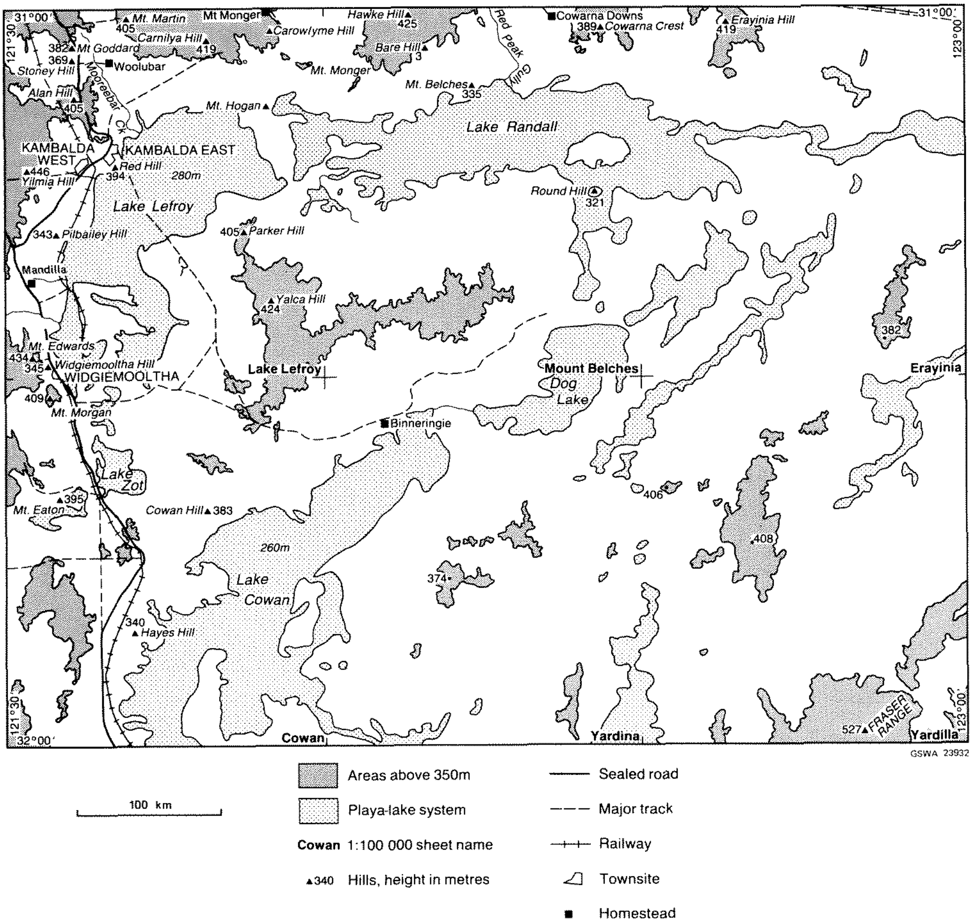

Figure 1. Major physiographic and cultural features of WIDGIEMOOLTHA SH 51-14

CLIMATE AND VEGETATION

The climate is semi-arid (mean annual rainfall of 280 mm) and there are no permanent fresh-water streams. A few widely scattered small swamps and gnamma holes retain fresh water through all but the driest periods.

The WIDGIEMOOLTHA area is mainly woodland (a major source of mine timber) interspersed with broad plains of saltbush and bluebush. Large areas are occupied by saline lakes and associated dune deposits. The dominant vegetation is eucalyptus woodland (salmon gum, gimlet and mallee), together with saltbush (*Atriplex*) and bluebush (*Kochia*). The lakes are bordered by saltbush and numerous varieties of samphire. Native pines (*Callitris*) occupy low areas adjacent to creeks and lakes, and spinifex (*Triodia*) is common on the dunes around eastern margins of playa lakes. Sandalwood is widespread, particularly on the granite soil, and is harvested for export to Asia. Newbey and others (1984) have carried out a biological survey of an area in the southeastern Goldfields that included WIDGIEMOOLTHA.

HISTORY OF INVESTIGATION

The first edition of WIDGIEMOOLTHA (Sofoulis, 1966) refers to previous publications that include reports on parts of the sheet. In the bibliography, Sofoulis included additional references to small mineral deposits, individual leases and holdings. The first edition geological map, together with the 1985 BMR aeromagnetic map, provided a basis for the intense nickel exploration activity in the 1960s and early 1970s. Much detailed geological work was carried out and was reported in company files, many of which are available from the Geological Survey of Western Australia.

Gemuts and Theron (1975) extended Williams' (1969) stratigraphic model for the southeastern goldfields, and outlined a stratigraphic and structural model for a large portion of the greenstones of WIDGIEMOOLTHA. These formed the basis for much subsequent work. Their compilation included a 1:250 000 scale geological interpretation that was compiled from the results of nickel exploration by various companies (Woodall and Travis, 1969; and unpublished company data), and university-based studies (McCall, Braybrook and Middleton, 1970; Campbell and others, 1970; Glikson, 1971a,b; Hallberg, 1972; Hallberg and Williams, 1972; McCall, 1969; McCall and Doepel, 1969; Nesbitt, 1971; O'Beirne, 1968; Oliver and others, 1972; Williams, 1972; and Williams and Hallberg, 1973). Other contemporaneous publications document additional work on WIDGIEMOOLTHA (Dunbar and McCall, 1971; Cox and Tyrwhitt, 1975; Dalgarno, 1975; INAL (International Nickel Australia Limited) staff, 1975; and Andrews, 1975). Papers by Ross and Hopkins (1975), and Marston (1984), highlight the important role that was played by the Kambalda nickel deposits (and associated ultramafic flows) in understanding volcanic-peridotite (komatiite) associated deposits.

Western Mining Corporation at Kambalda has continued to provide a stimulus to research on the geological evolution of this part of WIDGIEMOOLTHA (Gresham and Loftus-Hills, 1981) and on volcanic-peridotite associated nickel sulphide deposits (Marston and others, 1981; and a Special Issue of Economic Geology, volume 76, No.6, 1981). Research at universities both in Australia and overseas, based on fieldwork on WIDGIEMOOLTHA, has led to interesting and significant dicussions of Archaean crustal evolution (Archibald, 1979; Archibald and others, 1981; Binns and others, 1976; Chauvel and others, 1985; Claoué-Long and others, 1984; Fletcher and others, 1984; McCulloch and Compston, 1981).

Excursion guidebooks (Groves and Gee, 1980; Groves and Lesher, 1982; and Muhling, 1983) include some of the most recent interpretations of WIDGIEMOOLTHA geology. In recent years the emphasis has been on gold exploration and mining, and publications reflecting this trend are starting to emerge (Phillips and Groves, 1983; Witt and Swager, 1987).

Developments in isotopic dating using the Sm–Nd system have produced some interesting new data (McCulloch and Compston, 1983; Claoué-Long and others, 1984; Chauvel and others, 1985; Compston and others, 1985).

ARCHAEAN GEOLOGY

Introduction

The Archaean rocks of WIDGIEMOOLTHA are typical of the Eastern Goldfields Province (Griffin, in press). They include greenstones comprising metamorphosed and multiply-deformed sequences of mafic and ultramafic volcanic rocks, felsic volcanic rocks and associated volcaniclastic, clastic, and minor chemical sedimentary rocks. Banded iron-formation is rare. Mafic sills are widespread. A variety of granitoid phases, now generally foliated, intrude the greenstones. Gneiss is a minor rock type, restricted to the margins of some granitoid bodies in western WIDGIEMOOLTHA. Greenstones predominate on WIDGIEMOOLTHA and the best exposures are in the western part, where there are major mafic and ultramafic sequences.

Isotopic dating, discussed later, indicates that the Archaean rocks on WIDGIEMOOLTHA formed in the period 2.8 to 2.5 Ga. The basement on which the greenstones were deposited is unknown.

The lowest rocks in the succession are metamorphosed mafic and ultramafic volcanics. These are overlain by metamorphosed felsic volcanics and volcaniclastics. Metamorphosed clastic sedimentary rocks dominate the highest stratigraphic levels. Elements of this broad stratigraphy are present throughout WIDGIEMOOLTHA.

Metamorphism is generally greenschist to low-amphibolite grade.

Multiple deformation involving isoclinal folding affected most rocks and the structure is dominated by strong north-northwesterly trends.

Greenstones

Metamorphosed mafic and ultramafic volcanic rocks (Ab, Abm, Abt, Aku)

Mafic and ultramafic volcanic rocks dominate western WIDGIEMOOLTHA and are part of the greenstone sequences that contain the major mining centres of Kalgoorlie, Kambalda, and Norseman. Primary structures and textures are preserved in most areas, particularly where the rocks are little deformed and are metamorphosed in greenschist facies. These preserved features indicate that the rocks are derived from mafic and ultramafic flows, or mafic sills. In zones of high strain and higher metamorphic grade, primary features are generally obliterated.

Nomenclature of the mafic–ultramafic rocks, using a three-group classification, is based largely on field criteria; metamorphism, alteration, and weathering generally make chemical classification very difficult. The three groups are metakomatiite, metamorphosed high-Mg basalt, and metatholeiite.

Metakomatiite is ultramafic rock characterized by platy ‘spinifex’ texture after olivine. It comprises talc, serpentine, tremolite, and chlorite.

Metamorphosed high-Mg basalt is mafic rock characterized by fibrous amphibole after acicular pyroxene, and often containing variolitic (or ocellar) textures. It comprises tremolite–actinolite, chlorite, and plagioclase.

Metatholeiite is aphyric or plagioclase-phyric mafic rock dominated by actinolite–hornblende and feldspar.

This field classification roughly coincides with the chemical classification of Arndt and Nisbet (1982) for komatiite (MgO >18%) and komatiitic basalt (equivalent to metamorphosed high-Mg basalt) (MgO 9–18%).

Redman and Keays (1985) have subdivided the metabasalts in the Kambalda–Widgiemooltha area using chemical and petrographic criteria. They relate the subdivisions to both mantle heterogeneities and variations in the degree of melting and the amount of melt removed.

The metabasalts (both tholeiitic and high-Mg types) occur with metakomatiite, and dominate the lowest parts of the greenstone sequences. The combination of lava pillows and thin, interflow sedimentary rocks, indicate that these volcanic rocks were deposited in a subaqueous environment.

Metakomatiite (Aku)

Metakomatiite occurs as metamorphosed ultramafic flows which may be interlayered with other greenstone lithologies. Some thick flows are zoned; they consist of a lower cumulate part with an olivine peridotite composition, and an upper part with platy 'spinifex' texture, lower MgO content, and picritic composition (Ross and Hopkins, 1975). Quenching may have occurred at both the top and bottom contacts of the flow and preserved primary magmatic compositions (Groves and Lesher, 1982). Gresham and Loftus-Hills (1981) presented chemical and mineralogical details of a 147 m thick flow at Kambalda.

Metakomatiite on WIDGIEMOOLTHA consists of various combinations of tremolite, chlorite, serpentinite (antigorite), magnetite, talc, and carbonate. Metamorphic olivine and clinopyroxene are present in higher grade rocks. Relic primary igneous pyroxene and olivine are rarely seen. Platy olivine spinifex textures are pseudomorphed by secondary minerals.

The metakomatiite flows are usually 1 to 10 m thick, but some are over 100 m thick. The richer nickel-ore zones at Kambalda are generally associated with thick metakomatiite flows (Gresham and Loftus-Hills, 1981). Thin, fine-grained metasedimentary rocks occur between some flows (Fig. 2). Metakomatiite flows, in the Kambalda area, form a distinct unit within metamorphosed mafic flows. The total thickness of this ultramafic unit at Kambalda ranges from 0 to 1000 m (Gresham and Loftus-Hills, 1981). At Wannaway, west of the Widgiemooltha Monzogranite stock, the metakomatiite unit is 80–200 m thick and consists of at least nine flows (Marston, 1984).

Metabasalt (Ab)

The areas of metabasalt on WIDGIEMOOLTHA include mafic schist, amphibolite, and minor occurrences of dolerite. The dominant metabasalt is metamorphosed high-Mg basalt (*Abm*). Most areas of metabasalt are poorly exposed, strongly deformed, or include rocks at amphibolite grade. The area northwest of Widgiemooltha contains metamorphosed tholeiitic basalt containing vesicles and pillow structures. Areas of metabasalt in north–central WIDGIEMOOLTHA contain significant metamorphosed tholeiitic basalt. Metamorphosed tholeiitic basalt forms a minor component in areas of metamorphosed high-Mg basalt.

Metamorphosed tholeiitic basalt is aphyric or plagioclase-phyric and consists mainly of plagioclase and actinolite, with subordinate quartz, carbonate, and chlorite. At the highest metamorphic grade, biotite and hornblende are the dominant mafic phases.

Hallberg and Williams (1972), and Hallberg (1972), described metamorphosed tholeiitic basalt as the major basalt type in several areas on west WIDGIEMOOLTHA; however, recent chemical data (Redman and Keays, 1985) support field mapping on WIDGIEMOOLTHA which shows that there is an abundance of metamorphosed high-Mg basalt in these areas.

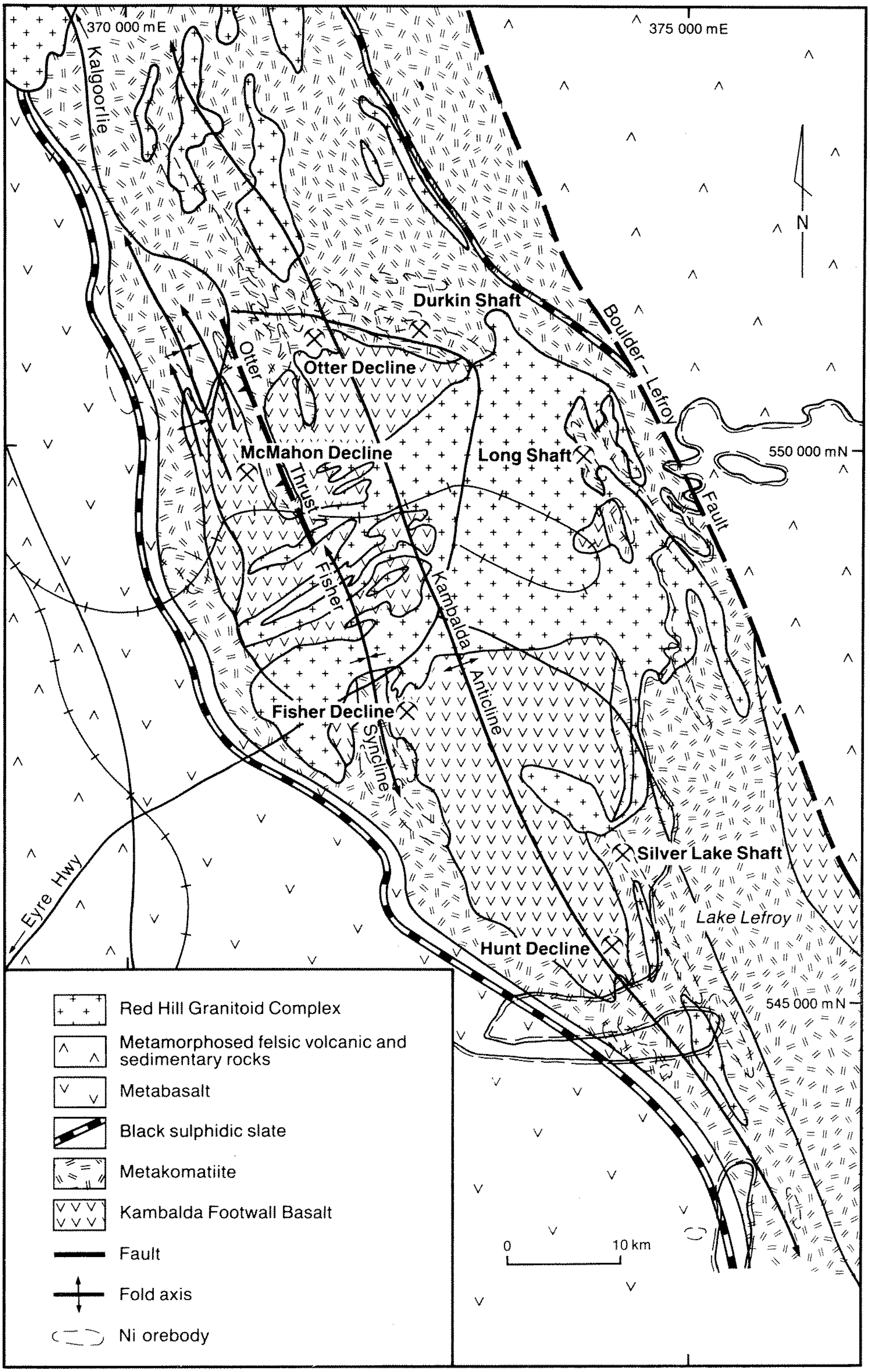

Figure 2. Interpretive geological map of the Kambalda area (after Marston, 1984)

In the stongly metamorphosed and deformed areas it is difficult to distinguish metabasalt from metadolerite sills, because the primary features have been destroyed, such as in areas east and southeast of the Victory–Defiance mine.

At Kambalda, and to the southeast through Jan mine to Tramways, east of Kay Dam, Kambalda Footwall Basalt (*Abt*) has been identified (Gresham and Loftus-Hills, 1981). It underlies nickel-bearing metakomatiite, and consists of metamorphosed tholeiitic basalt. It is a fine to medium-grained, dark-green rock comprising actinolite–tremolite, chlorite, calcite, albite, and minor amounts of epidote, biotite, hornblende, and quartz. Primary structures include numerous lava pillows, some flow-top breccias with a carbonate-rich matrix, and vesicular lava. Redman and Keays (1985) subdivided the Kambalda Footwall Basalt into an upper, low-magnesian part, and a lower, high-magnesian part.

Metamorphosed high-Mg basalt (Abm)

Metamorphosed high-Mg basalt dominates the mafic rocks on WIDGIEMOOLTHA, and is often spatially associated with metakomatiite and metamorphosed tholeiitic basalt.

'Spinifex' texture is common as a result of fibrous amphibole replacing acicular igneous pyroxene. Many outcrops of metamorphosed high-Mg basalt have a prominent variolitic texture. The pale variolites vary in size, between 2 mm and 20 mm in diameter, and may be irregularly distributed. In some exposures they are controlled by pillow morphology. They also coalesce to form large (30 mm) pale patches in the metabasalt. Pillow breccias are well exposed on the southeastern side of Lefroy Peninsula, 10 km northeast of Widgiemooltha.

The main minerals present are tremolite–actinolite, chlorite, together with minor amounts of plagioclase, carbonate, epidote, biotite, hornblende, and quartz.

Metamorphosed mafic and ultramafic intrusive rocks (Ao)

Mafic and ultramafic intrusive rocks include metadolerite (*Aod*), metagabbro, metanorite, metaferrogabbro (*Aog*), metaperidotite, and metapyroxenite (*Aou*). Most occur as sills within the mafic and ultramafic volcanic sequences, but some intrude metasedimentary rocks such as at Cutters Luck mine, northeast of Kambalda. These sills vary in thickness from a few metres to 1000 m, such as at Mount Monger. This 7 km long sill is also the longest sill on WIDGIEMOOLTHA. Deformation has disrupted the sill units in the Mount Monger and Yilmia Hill areas, causing offsets along strike and possible repetition by folding and tectonic interleaving (Griffin and others, 1983b).

The sills are metamorphosed, show subophitic textures, and are composed of tremolite–actinolite, hornblende, chlorite, and albite. Most of the larger bodies are differentiated, and the mineralogy is dominated in the ultramafic basal zone by metamorphic minerals such as chlorite, serpentine, talc, and tremolite. Relic textures and mineralogy include cumulus olivine and orthopyroxene in the basal zone; and orthopyroxene, plagioclase, and clinopyroxene in the upper mafic zone (McCall and Doepel, 1969; Williams and Hallberg, 1973). Rhythmic layering, involving plagioclase and actinolite (after pyroxene), is commonly seen in the thick gabbroic zones at Yilmia Hill.

The mafic and ultramafic sills are often seen adjacent to thin, grey and black slate units that probably provided a fissile zone into which the sills were preferentially emplaced. Thick sills acted as competent masses within the greenstone pile during deformation, and form open folds (e.g. Mount Monger and Stony Hill) resisting recrystallization and the development of cleavage. The strain has largely been absorbed by the surrounding rocks and in shear zones at the contacts.

The mafic–ultramafic sills are regarded as an integral part of the greenstone succession and were probably intruded during, or soon after, the major phase of mafic–ultramafic volcanism. Williams and Hallberg (1973), from field and chemical evidence, suggested that the sills are genetically associated with, and probably subvolcanic to, the metamorphosed high-Mg basalts.

Ultramafic schist (Au)

Many ultramafic rocks on WIDGIEMOOLTHA are schistose and lack primary features: these are shown on the map as ultramafic schist (*Au*). They are composed of tremolite, chlorite, carbonate and minor serpentinite, talc and magnetite.

Metamorphosed felsic volcanic rocks (Af)

Metamorphosed felsic agglomerate, flow-banded felsic lava, felsic tuff, and a variety of quartz–feldspar porphyries are widespread on WIDGIEMOOLTHA. Both extrusive and intrusive porphyry are recognized, although metamorphism and deformation make the distinction difficult.

Interlayered units derived from proximal volcaniclastic sedimentary rocks (such as metaconglomerate exposed on the Mount Edwards microwave-tower road, northwest of Widgiemooltha) are incorporated in this unit.

The metamorphosed felsic volcanic rocks are generally dacitic and consist of quartz, feldspar, minor sericite, chlorite (after biotite), carbonate, and pyrite. Quartz phenocrysts are embayed and subhedral. Feldspar phenocrysts are subhedral albite, and most feldspar is altered to clinozoisite, chlorite, and sericite.

Coarse angular clasts in metamorphosed agglomerate are indistinguishable from the matrix, except on some weathered surfaces, such as 2 km east of the Coolgardie–Esperance Highway on the Kambalda road. Flow banding is preserved in fine-grained porphyritic rocks south of Paris mine, south of Mount Hogan, and southeast of Hinamoa mine. Most laminated units, which are interbedded and spatially associated with the metamorphosed flows and agglomerate, are interpreted to be metamorphosed tuff beds. The original fine, fragmental texture is evident in some weathered exposures.

The largest areas of metamorphosed felsic volcanic rocks, in the northeast of WIDGIEMOOLTHA, are only mildly deformed and contain a weak foliation. They appear to have acted as competent masses, most of the strain having been taken up by the adjacent metasedimentary or mafic rocks.

The metamorphosed felsic rocks are interbedded with, and grade into, the metamorphosed sedimentary sequences. The felsic rocks are the most likely source for most of the sedimentary detritus.

At Kambalda, Widgiemooltha, and Hinamoa mine, the metamorphosed felsic volcanics overlie mafic–ultramafic sequences. In other areas, such as Mount Hogan and Paris mine, they are spatially close to the mafic–ultramafic sequences. The younging and structural data provide inconclusive evidence of stratigraphic position. The metamorphosed sedimentary rocks overlie these metamorphosed felsic volcanics. Metamorphosed felsic volcanic rocks are separated from mafic–ultramafic rocks in the Loves Find area by metasedimentary rocks.

By way of contrast, the metamorphosed felsic volcanics apparently underlie the mafic rocks east of Mount Monger homestead (Hickman, 1986). However, it is possible that this relationship is the result of tectonic stacking, not original stratigraphic superposition.

Minor metamorphosed andesitic volcanics occur with metamorphosed volcaniclastic sedimentary rocks, east of Mount Monger homestead (Hickman, 1986).

Felsic schist (Afs)

Quartz–feldspar–sericite schist is abundant throughout the greenstone sequence and contains minor amounts of chlorite, biotite, carbonate, and pyrite. Deformation and metamorphism have destroyed the primary textures which would enable these rocks to be classified as either metamorphosed felsic volcanic or sedimentary rocks.

Metasedimentary rocks (As)

Archaean metasedimentary rocks occupy large areas, especially in central and north central WIDGIEMOOLTHA. They also form significant, thin (less than 20 m), fine-grained units interlayered with the mafic–ultramafic rocks.

Pelitic and psammitic metasedimentary rocks (As, Asf)

Pelitic and psammitic metasedimentary rocks are generally deeply weathered, and outcrops are restricted to low country and around lakes. Large areas are interpreted from a distinctive mottled air-photo texture, and a vegetation pattern of open grassland with scattered eucalypts. Outcrop is generally sparse in these areas, but siltstone fragments occur in the soil. Such areas are shown on the map by the symbol $\frac{Czs}{As}$. The deep weathering pre-dates the deposition of Upper Eocene deposits, since trace fossils, such as burrows, can be observed in the metasedimentary rocks at several localities (Table 1). In some places these weathered rocks are silicified and the Eocene trace fossils and Archaean rock textures are well preserved.

The Mount Belches beds (*Asw*) are well-exposed turbidites associated with a prominent banded iron-formation at Mount Belches (Dunbar and McCall, 1971). The Mount Belches beds consist of biotite-bearing, metamorphosed, cross-bedded, graded, feldspathic sandstone, and interbedded laminated siltstone. Dunbar and McCall (1971) described the lithologies and their sedimentary structures in detail, attributing the sequence to deposition in a turbidite environment. These rocks are especially well exposed on the northern shore of Lake Lefroy. Reverse grading occurs in some places, demonstrated by coarse metamorphic biotite (after fine-grained pelite) at the top of the bed, grading to fine biotite in the coarse, quartz-rich base of the bed. Metamorphosed, felsic, volcaniclastic sedimentary rocks occur within the metasandstone, 50 m below a prominent banded iron-formation, south of Randalls mine.

TABLE 1. FOSSIL AND TRACE-FOSSIL LOCALITIES

Locations on Widgiemooltha map sheet	*Fossil type*	*Rock unit*	*Remarks*
1	Trace fossil: filled tubes 5–10 mm diameter, concave layered 'back-fill'; curved and variable orientation	Silicified, kaolinized, meta-quartzofeldspathic sandstone	Weathered Archaean schist invaded by organisms in Tertiary
2	Trace fossil: similar to 1, but less abundant; associated with calcareous cement in tree-root channels	Kaolinized meta-quartzofeldspathic sandstone	As for 1
3	Trace fossil: similar to 1, but less abundant	As for 2	As for 1
4	Corals, sponge spicules; well preserved solitary and composite corals	Eundynie Group bioclastic calcarenite	Princess Royal spongolite; quartz-pebble conglomerate beneath calcarenite
5	Sponge spicules	Eundynie Group ferruginous siltstone and sandstone on spongolite	Princess Royal Spongolite; laterite cap
6	Sponge spicules	Eundynie Group siltstone	Princess Royal Spongolite; laterite cap
7	Sponge spicules	Eundynie Group siltstone	Princess Royal Spongolite; 7m of exposure
8	Trace fossil	Siltstone	Probably weathered Archaean metasiltstone
9, 10, 11, 12	Sponge spicules	Eundynie Group siltstone	Princess Royal Spongolite
13	Silicified wood Fragments	Eundynie Group siltstone	Part of the lower non-marine Eundynie Group
14, 15, 16, 17, 18	Shell beds	Eundynie Group bioclastic calcarenite	Norseman limestone (Cockbain 1968a)
19	Bryozoans, sponge spicules	Eundynie Group calcareous siltstone	Norseman Limestone and Princess Royal Spongolite
20	Bryozoans, foraminifera	Eundynie Group calcarenite	Norseman Limestone (Hooper, 1959; Cockbain, 1968a)
21, 22	Sponge spicules	Eundynie Group siltstone	Princess Royal Spongolite

NOTES: Sponge spicules are readily identified with a hand lens.

Some palynology work has been undertaken by exploration companies involved with the investigation of lignite and bituminous clays within these Early Eocene sediments.

Most metasedimentary rocks on WIDGIEMOOLTHA are derived from pebbly sandstone, sandstone, siltstone, and shale, many of which contain a high felsic-volcaniclastic component (*Asf*). Course, graded and cross-stratified sandy beds are widespread and are interbedded with laminated siltstone. Slump, scour, and flame structures are common.

The metasedimentary rocks range from low-greenschist to mid-amphibolite grade. They comprise quartz, feldspar, biotite, chlorite, sericite, and minor tourmaline. Mafic schist (*Asb*) outcrops adjacent to mafic–ultramafic rocks 18 km east of Killaloa in central south WIDGIEMOOLTHA. Minor occurrences of mafic schist are found in the Mount Martin–Carnilya Hill area. The mafic schist contains abundant hornblende and epidote in laminated sequences, and these are probably derived from mafic volcaniclastic sedimentary rocks.

At low metamorphic grades, deformed primary biotite is partly replaced by chlorite. At higher grades, secondary biotite replaces original clay minerals (such as at Mount Belches) and also defines the foliation. Coarse, random overgrowths of andalusite, staurolite, cordierite, garnet, kyanite, and muscovite indicate that the peak of metamorphism was associated with low strain, and post-dates the last major deformation event, at least in some areas. This can be seen east of Widgiemooltha, northwest of Kambalda, and over a large area northeast of Binneringie homestead.

The most studied area of metasedimentary rocks on WIDGIEMOOLTHA is at Mount Belches, south of the Trans Australian Railway line, where Dunbar and McCall (1971) interpreted the rocks as a sequence of turbidites. Metasedimentary rocks in other parts of WIDGIEMOOLTHA may be of similar origin, but they are poorly exposed, and no detailed sedimentology has been undertaken.

Metamorphosed volcaniclastic sedimentary rocks are particularly abundant in west WIDGIEMOOLTHA, adjacent to felsic schist and metamorphosed felsic volcanic rocks. They were probably deposited in submarine fans flanking felsic volcanic centres.

Slate, metamorphosed shale, and chert (Ash, Ach)

Slate, thin silicified metamorphosed black shale, and laminated chert, are abundant throughout the greenstone sequence. They also occur in the clastic metasedimentary rocks described above.

The chert (*Ach*) and shale (*Ash*) units are important marker horizons in many areas and are the only horizons which define mesoscopic folds. At the surface, they are less than 5 m thick (generally only 1–2 m), and consist of quartz, minor sericite, tourmaline, and pyrite. Mine workings and drilling indicate that the chert is the silicified surface expression of a variety of metamorphic rocks. These were derived from siliceous, chemical-sedimentary rocks, sulphide-rich shale, carbonaceous shale, fine-grained felsic volcanic and volcaniclastic rocks, and psammitic and pelitic metasedimentary rocks (Bavington, 1981). In some places these silicified rocks are in contact with major mafic sills (such as in the vicinity of Yilmia Hill). They have also been the locus of tectonic movements and many are strongly deformed.

Chert, carbonaceous rocks and (less abundant) thin, fine-grained chlorite- or amphibole-rich rocks, between mafic–ultramafic flows at Kambalda, were interpreted as three types of metasedimentary rocks by Bavington (1981). He considered them to be derived from both felsic and mafic–ultramafic sources, with exhalative addition of sulphur and chalcophile elements. Minor felsic volcanic material, associated with the mafic–

ultramafic flows, probably represents detritus from explosive eruptions of a distant felsic volcano.

The metasedimentary cherts represent periods of minor detrital influx in both volcanic and clastic sedimentary environments. At Mount Belches, Dunbar and McCall (1971) suggested that magnetite was continually precipitated, but ironstone horizons accumulated in the deep water only when there were no turbidity currents depositing clastic sediments.

Banded iron-formation (Aci)

The most prominent banded iron-formation (BIF) is the Santa Claus Ironstone member, part of the Mount Belches beds (Dunbar and McCall, 1971). It consists of quartz, magnetite, and grunerite, and outlines north-plunging chevron folds in central–north WIDGIEMOOLTHA. Two major units of BIF, each 2–3 m wide, and several minor units, occur over a total thickness of 10 m.

The folds defined by the BIF plunge steeply north, and are tighter to the west where both fold limbs strike northward. Isolated BIF, east and northeast of Randalls mine, may be part of the Santa Claus Ironstone member as they are within rocks that appear to be equivalent to the Mount Belches beds. Alternatively, they may represent similar lithologies at different stratigraphic positions within the metaturbidites.

Banded iron-formations also occur 9 km southeast of Mount Monger, 10 km west of Cowarna Downs homestead, at several places southwest of Lake Randall, and in a screen of country rock between granitoids in the northeast of WIDGIEMOOLTHA. BIF was not seen in the greenstone belts that are rich in mafic–ultramafic rocks in west WIDGIEMOOLTHA.

Minor outcrops of metasedimentary rocks, too small to be shown on the map, include silicified dolomites mapped by Archibald (1979) near Widgiemooltha.

Merougil Beds (Asm)

The Merougil beds are a 2300 m thick unit of mainly metamorphosed, trough cross-bedded pebbly sandstone which is well exposed in the southeast plunging Merougil Syncline, 6 km west of Kambalda. The western limb of the syncline is steep and overturned in the south. Further outcrop is found to the southeast, on the eastern side of the Lefroy Peninsula.

The basal unit of the Merougil beds is 300 m thick and consists of schistose, interbedded sandstone and siltstone. The rock is a spotted, quartz–feldspar–biotite–chlorite schist. The spots (2–4 mm) consist of quartz and minor feldspar surrounded by biotite, which possibly replaces andalusite. This unit has a sheared basal contact that overlies a coarse, strongly cleaved metaconglomerate, which is dominated by felsic volcanic clasts. The schistose, spotted siltstone is overlain conformably by a succession of metamorphosed, trough cross-bedded pebbly sandstone and conglomerate. The sandy component is poorly sorted and contains clasts of quartz, feldspar, and small rock fragments, in a matrix of fine-grained quartz, muscovite, and biotite.

Rounded pebbles and cobbles generally occur at the base of thick-bedded units which grade upwards to a fine metasandstone containing metamorphic and primary biotite. The clasts include porphyry, granodiorite, chert, metasedimentary rocks, and less abundant mafic and ultramafic volcanics (McCall and others, 1970). Over half the pebbles are feldspar–quartz–biotite schist of metasedimentary origin. Sedimentary structures include graded bedding, cross-bedding, scour channels, and ripple marks.

Deformation fabrics are not obvious in the coarse metamorphosed sandstone and pebbly sandstone, but in some places the pebbles are aligned parallel to the regional cleavage, which dips steeply west and strikes north-northwest.

The Merougil beds were deposited in a shallow-water (probably fluvial) environment which received clasts from a mixed provenance, indicating major uplift and erosion of pre-existing greenstones and granitoids. They overlie a highly deformed, metamorphosed felsic volcanic sequence that outcrops on headlands and islands on Lake Lefroy, south of Kambalda. This volcanic sequence includes metamorphosed dacitic volcanics, and metamorphosed felsic volcaniclastic sandstone and conglomerate (Groves and Gee, 1980). The Merougil beds in this report differ from the definition of McCall and others (1970) by excluding all metamorphosed felsic volcanic units. The transition from a felsic volcanic environment to a fluvial environment with a polymictic source area, is sharp, and indicates that the sheared base of the Merougil beds is located on a disconformity.

The presence of polymictic clasts indicates that the Merougil beds were deposited relatively late during the development of the greenstones. They post-date the accumulation of earlier greenstones (include pelitic and psammitic sediments), as well as granitoid intrusion and erosion, yet they pre-date at least the last strong regional north-northwest structures.

Age

An Archaean age for the greenstones on WIDGIEMOOLTHA is assigned based on regional geochronological studies in the Southeastern Goldfields Province (Turek and Compston, 1971; Compston and Turek, 1973; McCulloch and Compston, 1981; Claoué-Long and others, 1984; Fletcher and others, 1984; Chauvel and others, 1985). Most of the recent work has been based on the greenstones at Kambalda. Sm–Nd isochron ages range from 2790 ± 120 Ma (McCulloch and Compston, 1981) to 3200 Ma (3262 ± 44 Ma, Claoué-Long and others, 1984; and on the same samples, 3230 ± 120 Ma, Chauvel and others, 1985). Chauvel and others (1985) also obtained a Pb–Pb isochron age on these samples which gave an age of 2730 ± 30 Ma and a model age of 2700 Ma for associated sulphides. They argued that the younger age represents the age of formation of the volcanic sequence and that the Sm–Nd age is a function of mixing of at least two isotopically distinct sources. Compston and others (1984a) found xenocrystic zircon with U–Pb ages of 2500 Ma, 3100 Ma and <2700Ma. They interpreted these as relics of felsic rock assimilated by the basaltic magma, and regarded them as evidence of contamination of basaltic magma that is younger than 2670 ± 10 Ma. These basaltic rocks have been intruded by a mildly deformed phase of the Red Hill Granitoid Complex that has a U–Pb zircon age of 2660 ± 10 Ma (Compston and others, 1984b; Gresham and Loftus-Hills, 1981). A slightly older age is indicated by a Pb–Pb isochron age of 2720 ± 105 Ma obtained by Roddick (1984), who suggested that this represents either a metamorphic event, or the time of eruption of the metabasalts. Further work is required to resolve the conflicting data, however an Archaean age for the greenstones in the range 2600 to 2800 Ma appears likely. Greenschist metamorphism at Kambalda has been dated at 2610 ± 30 Ma by a Rb–Sr isochron (Roddick, 1984).

Stratigraphy

The most reliable stratigraphic sequence for a greenstone succession comes from the Kambalda area (Fig. 2), and this can be correlated, along strike, with the Kalgoorlie area (Fig. 3). Both areas have been the subject of extensive mining and geological investigation (Gresham and Loftus-Hills, 1981; Groves and Gee, 1980; Groves and Lesher, 1982; Griffin and others, 1983a,b; Keats, 1987). The lowest parts are dominated by metamorphosed mafic–ultramafic rocks, and the highest parts by metamorphosed felsic, volcanic and clastic sedimentary rocks.

The stratigraphic base of the greenstone succession is unknown. A thin marker unit, the Kapai Slate, overlies a distinctive, variolitic textured metabasalt unit, that in turn overlies a volcanic unit dominated by metakomatiite. At Kambalda, the thick Kambalda Footwall Basalt underlies the metakomatiite and is the lowest exposed unit. Felsic volcanic rocks, and felsic volcaniclastic sedimentary rocks, form a thick complex unit above the mafic–ultramafic rocks. They have similar lithologies to the Black Flag Beds at Kalgoorlie. Mafic and ultramafic sills intrude the greenstones, but are most common in the mafic–ultramafic units.

The Merougil beds are stratigraphically the highest rocks exposed. They represent a change in environment of deposition, from deep to shallow water, and include a range of clast lithologies not present in the underlying clastic sedimentary rocks. They correlate with the Kurrawang Conglomerate west of Kalgoorlie, but lack BIF clasts.

This stratigraphy can be traced to the southeast, across Lake Lefroy through the Victory–Defiance and St Ives–Foster areas, to the Tramways area east of Kay Dam (Gresham and Loftus-Hills, 1981). Further correlations of this stratigraphy to the Bluebush, Republican, and Democrat areas (Fig. 4) can be made, based on similar lithological sequences. These areas are located on a regional anticline and have curved faults, parallel to strike at the base of the succession, that placed rocks low in the succession in juxtaposition against rocks higher in the succession. The Boulder–Lefroy Fault east of Kambalda also disrupts the stratigraphy as it places metakomatiite against metamorphosed felsic volcanics and volcaniclastic sedimentary rocks (Figs 2 and 4).

Stratigraphic successions from elsewhere on WIDGIEMOOLTHA have thinner greenstone sequences, and, due to discontinous outcrop and complex folding and strike faulting, involve much interpretation. A stratigraphic succession similar to that at Kambalda exists in the vicinity of Widgiemooltha, where the main metasedimentary unit is also associated with metamorphosed felsic volcanic rocks and overlies a mafic–ultramafic unit. Faulting on the contact (particularly in the area of the old Spargoville nickel mine) disrupts the succession. This broad relationship holds for most areas of metasedimentary rock. However, the metaturbidites at Mount Belches, and the large area of metasedimentary rocks south of Lake Randall, cannot be placed into the broad stratigraphic succession. They could be late because there are no equivalent rocks known to be present early in the succession to the west. Alternatively, they may represent deposition in a basin, separate from the mafic–ultramafic dominated greenstones to the west, that has been subsequently juxtaposed. Their western contact with the mixed mafic sequence at Mount Monger is interpreted as a fault, because the regional anticlines at Mount Monger and Mount Belches plunge in opposite directions.

Quartz–muscovite schist (Alm)

Quartz–muscovite schist is mapped both as outcrop, and beneath cover in the southeast of WIDGIEMOOLTHA. It has a strong cleavage that parallels the Albany–Fraser Orogen. The schist is thought to have originated as part of the granitoid–greenstone terrain of the Yilgarn Craton, derived from either granitoid or sedimentary rocks.

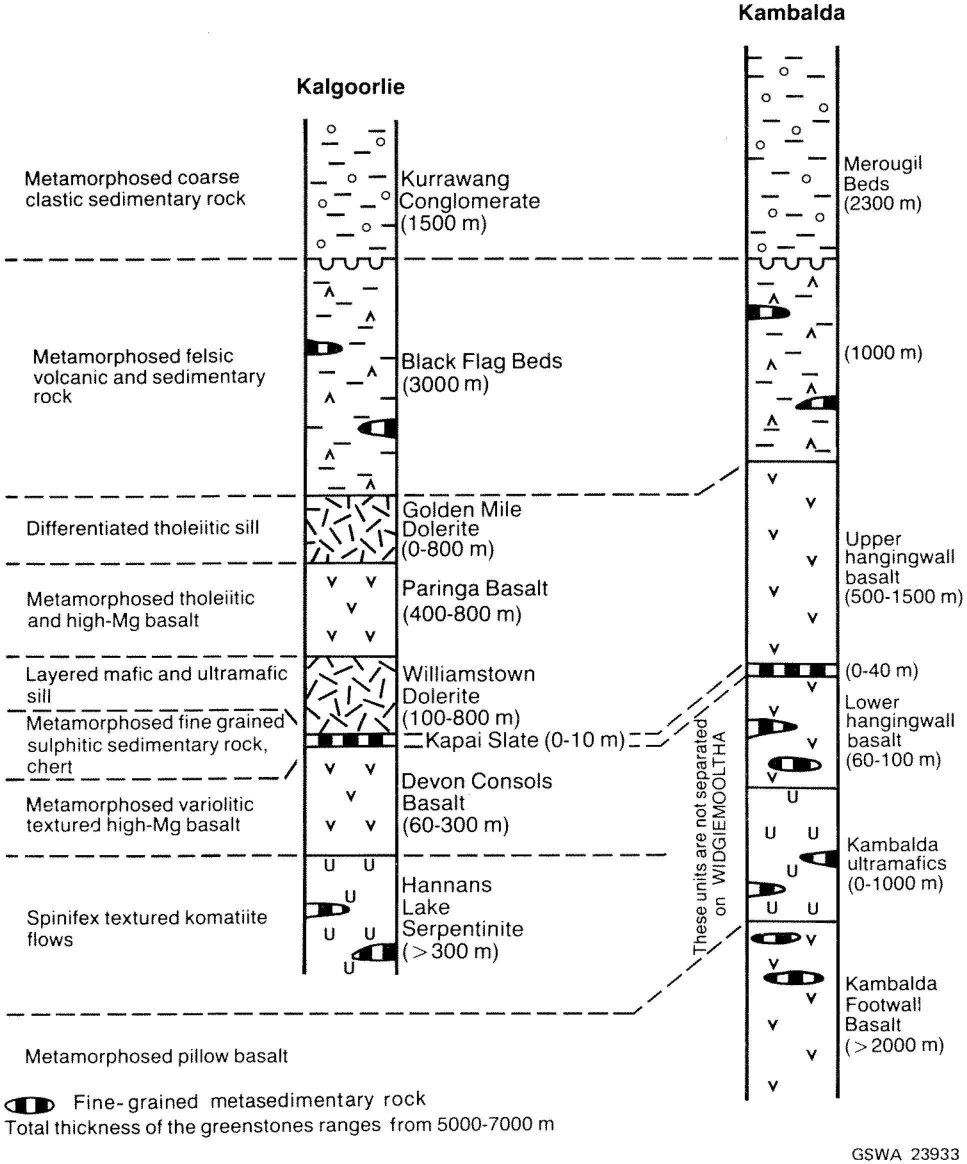

Figure 3. Stratigraphic correlation in the Kalgoorlie–Kambalda belt (after Groves and Gee, 1980; Gresham and Loftus-Hills, 1981)

Granitoid, gneiss, and syenite

Granitoid (Ag)

Granitoid rocks (*Ag*) occupy about one-third of WIDGIEMOOLTHA. They are very poorly exposed and extensive areas of granitoid are overlain by laterite and soil, particularly in the southeastern part of the sheet. Granitoid intruded all parts of the greenstone sequence except the Merougil beds. The majority of granitoid rocks show some evidence of recrystallization due to the influence of regional metamorphism.

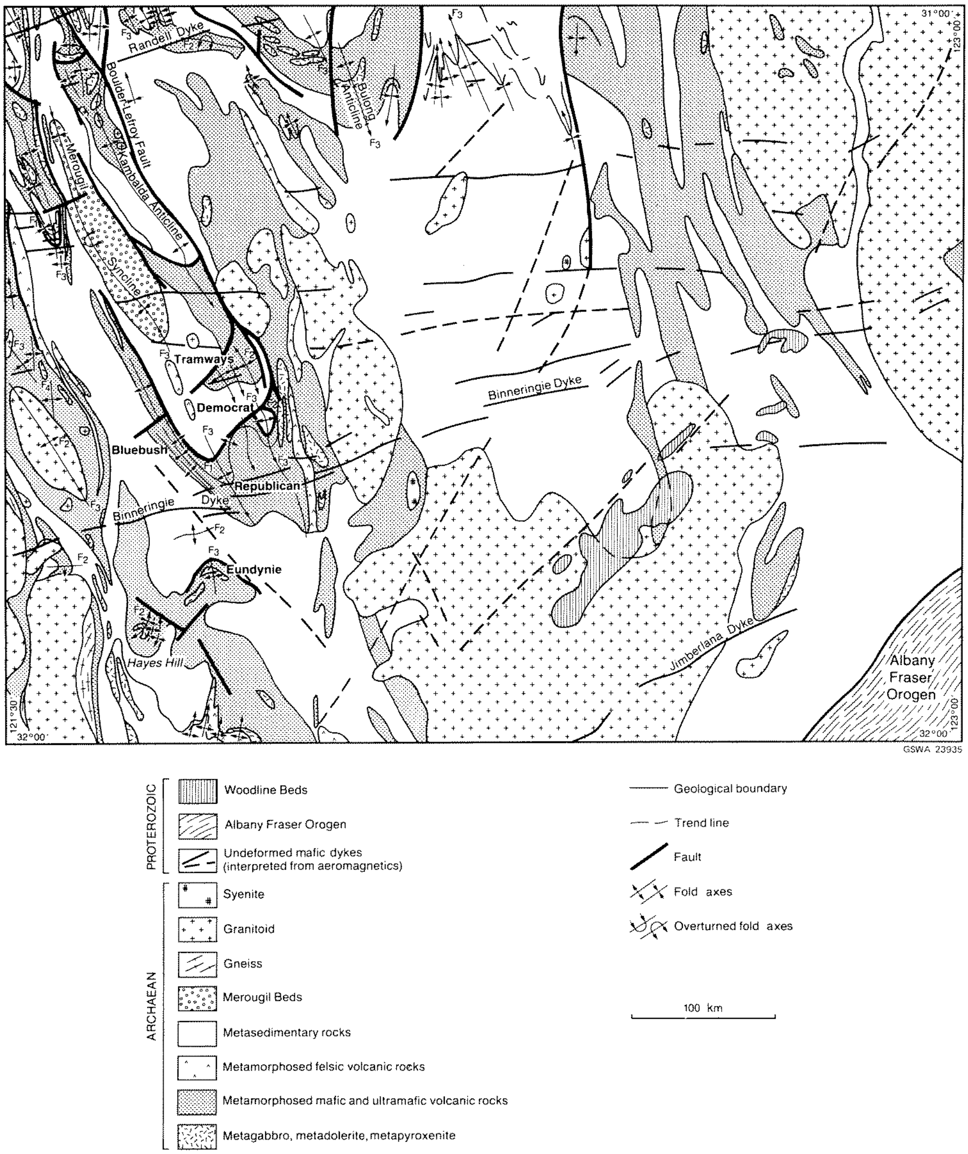

Figure 4. Geological interpretation of WIDGIEMOOLTHA

Regional variations in mineralogy and texture occur, but individual stocks cannot be recognized because the outcrop is sparse. Nevertheless, physiography, vegetation patterns, and aeromagnetic data, indicate that several of the granitoid bodies in the western half of WIDGIEMOOLTHA are ovoid (Fig. 4). Two such bodies are the Pioneer Granitoid Complex and the Widgiemooltha Monzogranite, which are located on the western edge of the Kalgoorlie–Norseman greenstone belt. Northwest of Binneringie homestead the granitoids have ovoid shapes, and are separated by screens of country rock. These granitoids are located on the contact between the major mafic–ultramafic sequence in the Yalca Hill–Parker Hill area, and the large tract of metasedimentary rocks to the east.

Screens of country rock in broad areas dominated by granitoid rocks are recognized by either aeromagnetic anomalies, or vegetation patterns. These are more likely to stand out if mafic rocks are involved. Small areas of metasedimentary rocks (pelitic rocks, not banded iron-formations) are unlikely to be noticed in large tracts of granitoid, and conversely, small areas of granitoid may not be recognized in areas of metasedimentary rocks. The latter applies to the poorly exposed, large area of metasedimentary rocks in the centre of WIDGIEMOOLTHA which does contain small granitoid intrusions and numerous tantalite-bearing pegmatite dykes in the south and east.

Most granitoid masses are composite, and show recrystallization textures and tectonic fabrics which make subdivision into individual stocks difficult, particularly where strain was heterogeneous and produced strongly foliated or gneissic margins around weakly deformed granitoid cores. One stock which has been recognized is called the Widgiemooltha Monzogranite (Fig. 4). It consists of deformed porphyritic monzogranite.

Most granitoid rocks are foliated, metamorphosed monzogranite, and contain minor amounts of syenogranite and granodiorite. They consist of quartz, oligoclase, alkali feldspar, and biotite, together with accessory apatite, sphene, zircon and opaque minerals. Microcline occurs as phenocrysts. Euhedral oscillatory zoning in plagioclase indicates that the granitoids are of magmatic origin.

Small intrusions of syenogranite, aplite, monzogranite, granodiorite, monzogranite porphyry, granodiorite porphyry (*Agf*), and pegmatite (*Agp*) are numerous in the greenstone sequences. They occur either as dykes, or as irregular masses, such as parts of the Red Hill Granitoid Complex in the Kambalda area.

The granitoid rocks are heterogeneously deformed. Both undeformed and strongly deformed rocks occur in individual plutons. Recrystallized biotite and quartz define a foliation.

The Erayinia Granitoid Complex (*Agy*) was intruded as several stocks that produced hornfels on the contacts with intervening screens of country rock. Foliated hornblende–biotite monzogranite is the dominant phase, with minor porphyritic granodiorite. Microcline phenocrysts, small biotite-rich xenoliths, generally undeformed pegmatite dykes, and quartz veins are widespread. The eastern contact is marked by a strong aeromagnetic anomaly over banded iron-formation, and its present shape probably results from later deformation of the original intrusive contact. The western contact is marked by a narrow hornfels zone in the mafic greenstones, and a minor aplite phase on the contact.

The poorly exposed Pioneer Granitoid Complex (*Agn*) is dominated by foliated biotite monzogranite, with abundant pegmatite intrusions, quartz veins, and zones containing xenoliths of gneiss.

The Red Hill Granitoid Complex (*Agrh*) outcrops as small irregular bodies and dykes within the mafic–ultramafic rocks at Kambalda and to the north. It consists of syenogranite, monzogranite porphyry, and granodiorite porphyry, which show, locally, cross-cutting relationships. The rocks of this complex have been affected by regional metamorphism, resulting in recrystallized biotite which defines a weak foliation (Ross and Hopkins, 1975; Gresham and Loftus-Hills, 1981).

The Widgiemooltha Monzogranite (*Agw*) is a foliated, and locally strongly lineated biotite monzogranite, which contains microcline phenocrysts. It has been deformed and metamorphosed along with the surrounding mafic–ultramafic rocks. Deformed dykes of the Widgiemooltha Monzogranite have intruded high-Mg basalt on the northeastern contact.

Pegmatite (*Agp*) and quartz veins (*q*) of several generations are a minor, but widespread, component of the granitoid rocks. They are also present within the mafic–ultramafic and metasedimentary parts of the greenstones, such as on the eastern contact of the Fifty Mile Tank Gneiss with mafic–ultramafic rocks, and in metasedimentary rocks north and northeast of Binneringie homestead. The pegmatites consist of quartz, feldspar, and muscovite, and minor amounts of biotite, lepidolite, tourmaline, tantalite, cassiterite, and beryl. Less deformed pegmatites consistently cut more deformed pegmatites which suggests that there were several episodes of pegmatite intrusion.

Age of granitoid

The granitoid rocks on WIDGIEMOOLTHA are Archaean. Most were deformed and metamorphosed contemporaneously with the greenstones. They are cut by undeformed mafic dykes, such as Binneringie Dyke and Jimberlana Dyke, which are discussed later.

The Rb–Sr ages which range from 2700 to 2550 Ma (Table 2) (de Laeter and others, 1981; Groves and Lesher, 1982), may largely reflect metamorphism (Roddick, 1984).

At Kambalda, Gresham and Loftus-Hill (1981) considered that a 'sodic granite' of the Red Hill Granitoid Complex was emplaced after one phase of deformation and metamorphism, but before further deformation and metamorphism. This rock was given an U–Pb zircon age of 2820 ± 15 Ma (Compston, 1980) but subsequently revised to 2660 ± 10 Ma (Compston and others, 1985) (Table 2).

Younger felsic dykes intrude the granitoid complex; Compston (1980) dated one of these at 2560 ± 30 Ma from zircon and total-rock U–Pb analysis.

Gneiss (An)

Gneiss is poorly exposed on WIDGIEMOOLTHA, except for the Fifty Mile Tank Gneiss (*Ang*), which is well exposed over an area 18 km long and up to 2.5 km wide, east of the Pioneer Granitoid Complex, in southwest WIDGIEMOOLTHA. Small areas of gneiss have also been mapped along the southwestern margin of the Pioneer Granitoid Complex, and on the edge of the greenstones, 13 km west of Redross mine, where they are associated with foliated granitoid. The Fifty Mile Tank Gneiss (*Ang*)

TABLE 2. ISOTOPIC-AGE DATA FOR GRANITOID ROCKS RELEVANT TO THE WIDGIEMOOLTHA SHEET

Age (Ma)	*Method*	*Reference*
KAMBALDA		
Red Hill Granitoid Complex 'sodic' granodiorite		
2760 ± 70	Pb–Pb isochron, granodiorite	Oversby, 1975
2514	Pb–Pb model K-feldspar, granodiorite	
2820 ± 15	U–Pb zircon, granodiorite	Unpublished data, Compston, 1980
2660 ± 10	U–Pb zircon, granodiorite	Compston and others, 1984a
2559 ± 35	Rb–Sr model microcline, sodic granite	Roddick, 1974
Other data on granitoid material		
2692 ± 80	Rb–Sr model plag + total rock	Roddick, 1974
2550	Rb–Sr model biotite	Roddick, 1974
2572	Rb–Sr model biotite	Roddick, 1974
2541 ± 35	Rb–Sr model microcline	Roddick, 1974
2592 ± 60	Rb–Sr isochron mineral + total rock	Roddick, 1974
Felsic porphyry dykes		
2560 ± 30	U–Pb zircon, felsic porphyry	Unpublished data, Compston, 1980
2710 ± 200	Pb–Pb isochron total rock	Roddick, 1974
2521 ± 40	Rb–Sr isochron total rock	Roddick, 1974
GRANITOIDS IN THE KALGOORLIE–NORSEMAN AREA		
2612 ± 13	Rb–Sr isochron total rock	Turek, 1966
2562 ± 20	Rb–Sr isochron total rock	Arriens, 1971
GRANITOIDS CLOSE TO THE WIDGIEMOOLTHA SHEET		
Mungari granite, 25 km southwest Kalgoorlie		
2565 ± 20	Rb–Sr isochron mineral + total rock	Compston and Turek, 1973
2665 ± 35	Rb–Sr model biotite	Compston and Turek, 1973
2640 ± 35	Pb–Pb isochron mineral	Oversby, 1975
2450	Pb–Pb model K-feldspar	Oversby, 1975
Karonie granodiorite, 112 km east of Kalgoorlie		
2691 ± 74	Pb–Pb isochron mineral	Oversby, 1975
2490	Pb–Pb model K-feldspar	Oversby, 1975
Buldania Rocks, 23 km east Norseman		
2655 ± 35	Pb–Pb isochron mineral	Oversby, 1975
2581 ± 20	Pb–Sr isochron total rock	Oversby, 1975
2550	Pb–Pb model K-feldspar	Oversby, 1975

is a component of the Pioneer Dome (Binns and others, 1976; Archibald and others, 1981; McCulloch and others, 1983). This dome is defined by generally poor outcrop of granitoid surrounded by greenstones. The gneiss and adjacent greenstones on the eastern side are relatively well exposed.

The Fifty Mile Tank Gneiss consists of two components that have distinctive patterns on aerial photographs: areas of dense vegetation with a streaky or banded appearance, and mottled areas that are poorly vegetated. They form broad, subparallel bands, usually 100 m to 300 m wide, parallel to the small-scale gneissic banding. On the ground the two patterns reflect different proportions of pegmatite veins parallel and subparallel to banding, but the boundaries between them are indistinct. The pegmatite veins range from a few centimetres to 4 m in width, are deformed, and locally make up more than 50% of the outcrop.

Gneissic banding consists of both light and dark fine-grained quartzo-feldspathic units which are indistinct in weathered outcrops. A strong foliation (which is defined by preferred orientation of biotite and biotite bands, and is generally parallel to the gneissic banding) appears, in some places, to cut (at a low angle) across an earlier compositional banding. Banding is sometimes marked by parallel mafic layers which are interpreted as deformed and recrystallized mafic dykes or sills. Strongly lineated gneiss on the eastern margin of Fifty Mile Tank Gneiss is attributed by Archibald (1979) to emplacement of the gneiss by solid-state diapirism. However, it is more likely that the foliation and lineation are related to fold interference structures which produced the Pioneer Dome.

Five phases of deformed pegmatite intrusion are recognized in the gneiss. Aplite dykes and small monzogranite-porphyry intrusions also occur. The early phases are parallel to, and partly define, the gneissic banding. These pegmatites are boudinaged, contain alkali-feldspar augen, show tectonic and metamorphic grain-size reduction, and are folded. The youngest pegmatites are only weakly deformed and are similar to the pegmatites that intrude the greenstones.

The banding of the gneiss is discordant with the foliation of the greenstone to the east, and the gneiss is intruded by late granitoid. The contact with the main Pioneer Granitoid Complex to the west is not exposed.

It appears that the Fifty Mile Tank Gneiss may either be surrounded by faults, or intruded by porphyritic monzogranite in the west. The porphyritic monzogranite that dominates the Pioneer Granitoid Complex lacks the foliation seen in the Widgiemooltha Monzogranite to the north, so may be a younger intrusion. The Fifty Mile Tank Gneiss is more strongly deformed than both the granitoids and the greenstones. It was probably tectonically emplaced into its present position before it was deformed and metamorphosed during the latest regional tectonic events.

Age of gneiss

Many authors have considered the gneiss to be basement to the greenstones and granitoids (Archibald and Bettenay, 1977; Gee, 1979; Archibald and others, 1978, 1981). However, recent Sm–Nd and Rb–Sr isotope studies (McCulloch and others, 1983) on samples from Fifty Mile Tank Gneiss and elsewhere in the Eastern Goldfields Province, and Pb–Pb studies (Bickle and others, 1983) on rocks from the Diemals area, 350 km northwest of Widgiemooltha, are inconclusive.

Samples from Fifty Mile Tank Gneiss give a three point Sm–Nd isochron of 2800 ± 150 Ma which agrees well with the Rb–Sr isochron age of 2780 ± 60 Ma derived from samples from a wide region of the Eastern Goldfields. McCulloch and others (1983) concluded from these analyses that the gneiss could be part of a craton that had been stabilized for less than 100 Ma prior to formation of the greenstones at 2720 ± 105 Ma (Pb–Pb isochron, Roddick, 1984), or 2790 ± 30 Ma (Sm–Nd isochron, McCulloch and Compston, 1981).

The field evidence is inconclusive. If the Fifty Mile Tank Gneiss is not basement to the greenstones, but is derived from intrusive granitoid, then it did not form in its present position, because the eastern contact with the greenstones is tectonically discordant. The rocks are either tectonically juxtaposed, or their primary contact was modified by tectonism. Younger granitoid phases have intruded the gneiss and greenstone, and destroyed previous contact relations.

Syenite

Syenite intrusions form two prominent outcrops: 10 km south-southeast of Binneringie homestead, on a peninsula of Lake Cowan, and 7 km north-northeast of the abandoned Madoonia homestead. Both intrude greenstones and granitoid. A swarm of parallel syenite dykes, individually less than 5 m wide, intrudes metamorphosed high-Mg basalt 18 km south-southwest of Mount Monger homestead. The syenites generally consist of porphyritic perthite in a medium to coarse-grained matrix of feldspar, aegirine-augite, abundant magnetite and sphene, together with accessory apatite and zircon. Syenite and small mafic dykes south-southeast of Binneringie homestead are affected by minor north–south shear zones, and the rocks have a schistosity defined by secondary chlorite. The syenites on WIDGIEMOOLTHA are late Archaean; they pre-date the Proterozoic mafic–ultramafic dykes and are probably similar in age to syenites in the northern parts of the Eastern Goldfields that have been dated as 2500 Ma (Rb–Sr isochron, Libby and de Laeter, 1981).

Structure

Folding

All Archaean rock units, except some of the small, late granitoid intrusions and quartz veins, are deformed. The rocks contain foliations, cleavages, and lineations that have a variety of orientations, but are dominated by a north-northwest trend. Mesoscopic folds are generally tight to isoclinal, and are particularly well preserved in pelitic metasedimentary rocks and fine-grained laminated siliceous units.

A generally weak cleavage, parallel to bedding, has been folded by subsequent deformation in the Republican area, 5 km northeast of Cowan Hill. Regional-scale folds are clearly defined by lithological trends on WIDGIEMOOLTHA, particularly the anticlines at Mount Monger, Mount Belches, and Kambalda, and the syncline in the Merougil Creek area. Plunges on these structures vary from moderate to steep. Fold interference patterns are apparent in the Hayes Hill area. The greenstones throughout WIDGIEMOOLTHA have a strong, steep cleavage which shows a preferred north-northwest trend; this trend is also reflected in major folds and faults.

Recumbent folding (D_1) is the earliest of four deformation events that were recorded by Archibald and others (1978, 1981) from an area southeast of Widgiemooltha, and by Gresham and Loftus-Hills (1981) from the Kambalda area. Gresham and Loftus-Hills (1981) recorded a weakly developed, layer-parallel fabric, S_1. The most prominent D_1 structure is an anticline in the Republican–Bluebush area that was refolded by a later event which produced the prominent regional folds.

The D_2 event was a mild, long-wavelength event with a steep east to east-northeast trending axial surface. Fabrics associated with this event appear to have been masked by later, strongly penetrative deformation. D_2 folds are present in the major structures in the Tramways and the Hayes Hill area, and the greenstones north of the Pioneer Granitoid Complex. D_2 may be equivalent to some of the F_3 structures of Gresham and Loftus-Hills (1981), which they suggest are asymmetric folds whose northern anticlinal limbs are steeper than southern limbs. The overturned anticline south of Carnilya Hill is possibly a D_2 structure (Fig. 4).

The D_3 deformation was an intense, tight-folding event, resulting in a steep north-northwest-trending axial surface. It dominated the regional structures and produced a well developed S_3 fabric, present in all Archaean rock types. Interference with D_2 caused the plunge reversals on these north-northwest-trending folds. The D_3 event was also responsible, in part, for the pattern of ovoid granites surrounded by greenstones, particularly the domal structures in the southwest of WIDGIEMOOLTHA, such as the Widgiemooltha Dome. Alternatively, Archibald and others (1981) argued that the fabrics in the Widgiemooltha Dome, and adjacent greenstones, resulted from solid-state diapiric emplacement of granitoid. D_3 is equivalent to F_2 of Gresham and Loftus-Hills (1981) and D_2 of Archibald and others (1978, 1981). The relative timing of D_2 and D_3 is unclear; the two events may have been closely related, which would mitigate against the preservation of D_2 fabrics, particularly if D_2 was mild.

Subsequent deformation is recognized at Kambalda by Gresham and Loftus-Hills (1981) in the form of open upright F_4 folds which have south-plunging axes. Swager (1989), from work at Kalgoorlie, recognized steep-dipping north-trending folds which he attributed to sinistral movement of the Boulder–Lefroy Fault during the later part of the D_3 event. North–south folds on WIDGIEMOOLTHA may be of similar origin, particularly those structures adjacent to the Boulder–Lefroy Fault. In the southeast of WIDGIEMOOLTHA, Archibald and others (1978, 1981) recognized two folding events that trend north to north-northwest. The planar fabrics associated with these are steep-dipping, and generally parallel to lithological layering. They probably include both S_1 and S_3; much of the variation in direction may be due to interference by D_3 on S_1. However, crenulation of S_3 does occur in some high-strain areas adjacent to the granitoid margins, which indicates a post-D_3 event, roughly parallel to D_3.

Faulting

The most prominent fault is the Boulder–Lefroy Fault which extends from Kalgoorlie, southeastward to beyond the St Ives area (Figs 2 and 4). Although in general it is not exposed, it is identified by minor shearing in areas where there are sharp terminations of lithological trends (Fig. 2). In the mine areas of Hampton–Boulder (New Celebration) and Jubilee, the Boulder–Lefroy Fault is a zone of shearing up to 300 m wide, which includes gold-mineralized porphyry, and ultramafic schist containing quartz veins. Sinistral movement of 10 km has been determined on this fault and it has been interpreted by Swager (1989) as a major wrench structure related to the strong D_3 event. Similar north-northeast-trending strike-slip faults are mapped to the east.

Significant north-trending faults occur in north–central WIDGIEMOOLTHA. These are poorly exposed and their presence inferred largely to account for major contrasts in lithology and structural style in adjacent areas. For example, the north-northwest-plunging structure at Mount Belches is adjacent to the large south-plunging anticline at Mount Monger. The folds in the metaturbidites near the fault contact tighten to isoclinal structures, and the transition to mafic rocks of the Mount Monger anticline is masked by laterite (Fig. 4).

An early suite of faults is recognized, and these have been folded by D_3 folds. They are most prominent in the open D_3 Kambalda Anticline, both north of Jan mine (20 km southeast of Kambalda), and in the Democrat–Republican area (Fig. 4). In both these areas the faults are parallel to early tight-to-isoclinal folds (interpreted as recumbent D_1), and have been folded by the D_1 event. Consequently, these faults may represent early thrust faults associated with the D_1 event.

Conclusions

The geological interpretation presented in Figure 4 is not comprehensive, but presents only the more obvious features. The major regional deformation event that produced the pervasive north-northwest fabrics, largely coincided with the peak of metamorphism. It post-dated all Archaean sedimentation and volcanism, and most of the granitoid intrusion. The details of earlier deformation and granitoid intrusion events are not well known. The Merougil beds (late in the greenstone sequence) indicate that metasedimentary rocks and granitoid had already been exposed and eroded prior to the major period of deformation and metamorphism. It is possible that the earliest granitoid intrusion into the lowest mafic parts of the succession was related to the extensive felsic volcanism. This close relationship between granitoid intrusion and felsic volcanism is apparent in the Laverton–Leonora area to the north (Hallberg, 1986).

Early recumbent folds, and associated faults parallel to bedding, may have caused major disturbance of the stratigraphic sequence. The extreme attenuation of the mafic and ultramafic greenstones in the Bluebush area (Fig. 4) is largely a result of D_1, further enhanced by D_3. Terminations of greenstone lithologies on WIDGIEMOOLTHA occur by attenuation as well as through folding, cross-faulting, or facies changes. In addition, the geology on a detailed scale is characterized by repetition of contrasting schistose lithologies. This complex geology is illustrated in the ore zones at Kambalda (Gresham and Loftus-Hills, 1981), yet the Kambalda Dome is a relatively broad, open structure in comparison to other areas of well-exposed greenstones. The complex folding in the Mount Belches area would probably not be recognized if it were not for the well-exposed BIF. Similar complex folding in areas of poor exposures probably remains undetected. These features result in a poorly constrained greenstone stratigraphy on WIDGIEMOOLTHA, with only very broad correlation possible with the Kalgoorlie–Kambalda succession.

A cyclic stratigraphic succession has been proposed for the Kalgoorlie–Norseman region by Gemuts and Theron (1975). However, it seems that much of the structural complexity was overlooked by them, or considered to be irrelevant to the simple, broad, syncline–anticline model they presented. Apparent cyclicity could have resulted from early tectonic stacking. Griffin and others (1983a) outlined an alternative model based on a single sequence of development which involved facies variations and a complex history of deformation. The earliest stratigraphic unit is dominated by mafic and ultramafic volcanics. This is successively overlain by felsic volcanic rocks, and clastic sedimentary rocks. The greenstones on WIDGIEMOOLTHA, in particular those in the west, reflect this apparent simple succession. The repetition and dislocation of units and successions is interpreted as the result of substantial deformation involving tectonic interleaving and recumbent folding. Further disruption to the continuity of units has been caused by the intrusion of granitoid plutons. The individual greenstone belts, in particular those parts dominated by mafic–ultramafic lithologies, may have originally developed in separate zones or basins, but in a broadly similar way to an adjacent zone. The separation may have been significant, or alternatively, it could have allowed for some overlap of the greenstone sequences from one zone to another. This overlap resulted in apparent alternating bimodal volcanism of ultramafic and felsic lavas. Development of differing greenstone sequences in separate basins, has been outlined by Hallberg (1986) for the Laverton–Leonora area. The sedimentary basins would have formed as volcanism waned and the zones were brought together to produce an expansive area of greenstones.

This model of Griffin and others (1983a) is based on parts of the greenstone sequence proposed by Groves and Batt (1984) to have accumulated in one major rift, the Norseman–Wiluna zone. The Archaean greenstones on WIDGIEMOOLTHA are not necessarily indicative of a major rift zone.

The identification of basement underlying the greenstones is unresolved. The Fifty Mile Tank Gneiss is possibly a remnant of sialic basement, although it could equally represent a tectonic fragment of a strongly veined and deformed intrusive granitoid from within the greenstones.

PROTEROZOIC GEOLOGY

During the Proterozoic a major layered-basic body, the Fraser Complex, was intruded and deformed in southeast WIDGIEMOOLTHA, and major suites of mafic and ultramafic dykes intruded the crystalline Archaean crust. Those suites with an easterly trend are well exposed; however, the northeasterly and northwesterly trending suites are identified only on aeromagnetic maps. During the Proterozoic the Archaean crust was eroded, and mainly clastic sediments deposited to form the Woodline Beds.

Albany–Fraser Orogen (*Pa*)

Part of the Albany–Fraser Orogen (*Pa*) is exposed in a prominent range of hills in the southeast corner of WIDGIEMOOLTHA. These rocks were intensely deformed between 1800–1100 Ma (Wilson, 1969; Myers, 1985). The major component of this orogen on WIDGIEMOOLTHA is the Fraser Complex, consisting largely of pyroxene granulite, derived from a layered, basic igneous intrusion (Myers, 1985). This igneous body has been highly deformed and tectonically interleaved with metasedimentary rocks (*Pas*), intruded by granitoid (*Pag*), and the whole assemblage has subsequently been further metamorphosed and deformed (Myers, 1985). The metasedimentary rocks are mainly quartz–garnet–feldspar schist containing prominent manganese oxide bands in some places. The metamorphosed granitoid is generally a mylonitized garnet syenogranite and contains feldspar augen.

Garnet amphibolite (*Paf1*) is equivalent to Unit 1 of Myers (1985) and may contain some mafic Archaean greenstones as well as the metagabbro of the Fraser Complex.

The mineralogy indicates amphibolite-facies metamorphism with evidence of retrogression from granulite facies.

Mafic granulite with a low magnetic response (*Paf2*) corresponds with Unit 2 of Myers (1985), and *Paf4* is a mafic granulite with a moderate magnetic response and corresponds to Unit 4. Unit 3 of Myers (1985) does not outcrop on WIDGIEMOOLTHA.

Sharp magnetic breaks and lineaments on air photos support the tectonic breaks recognized between these units by Myers (1985). The rocks closest to the northwestern contact of the Albany–Fraser Orogen are biotite–feldspar–quartz schist and could be derived from either the Archaean metasedimentary rocks further to the northwest, or the deformed Archaean granitoid as seen on the Eyre Highway to the south on NORSEMAN, and to the northeast on ZANTHUS. The fabrics in the schist parallel those in the Albany–Fraser Orogen, and Myers (1985) describes the margin as a zone of intense ductile deformation.

The age of intrusion of this large, layered, mafic body is unknown, but could be as old as Archaean. The age of the deformation spans the period 1800 to 1100 Ma. Myers (1985) describes an undeformed dyke (along strike from the 2400 Ma Binneringie Dyke) that cuts the Fraser Complex.

If this dyke is indeed part of the Binneringie Dyke, then the Fraser Complex is much older than the ages obtained from the metamorphic minerals to the south.

Mafic and ultramafic dykes (*Pdy*)

Undeformed Proterozoic tholeiitic dykes, mainly of gabbro, but varying from pyroxenite to granophyre, occur with a general east–west trend and intrude the granitoid–greenstone terrain throughout WIDGIEMOOLTHA. They were called the Widgiemooltha Dyke Suite by Sofoulis (1966). Some form prominent ridges (such as at Cowan Hill, where the Binneringie Dyke reaches a maximum thickness of 3 km); and some are completely buried by surficial deposits. The extent and distribution of these dykes can only be obtained from detailed aeromagnetic surveys. They are widespread and, although there is little or no outcrop, some of the largest dykes produce prominent linear anomalies.

The Binneringie Dyke (*Pdyb*) is the most prominent dyke and is best exposed in a chain of hills along the northern shore of Lake Cowan. It can be traced discontinuously for 600 km across the full width of the Yilgarn Block, from the Albany–Fraser Orogen to the Western Gneiss Terrain.

Southwest of Binneringie homestead, the Binneringie Dyke has a contact metamorphic aureole in which granitoid is hornfelsed and minor melting occurs in a zone several metres wide. Felsic rock occurs in the centre of the Binneringie Dyke 11 km southeast of Binneringie homestead. McCall and Peers (1971) interpret this felsic rock as a late granophyric phase of the dyke, but the composition and field relations of these rocks suggest that it is hornfelsed granitoid. Metasedimentary rocks and metamorphosed felsic volcanic breccias enclosed by the Binneringie Dyke, south of Cowan Hill, are described by McCall and Peers (1971).

McCall and Peers (1971, p. 1182) note that Binneringie Dyke differs from the Jimberlana Dyke (Campbell, 1978), by having only vertical layering.

The easternmost part of another major intrusion called the Jimberlana Dyke (*Pdyj*) outcrops in southwest WIDGIEMOOLTHA. It has well-developed rhythmic layering and 'canoe' structures, as well as vertical layering. It is discussed in detail by Campbell (1978).

The Celebration and Randalls dykes (*Pdyc*, *Pdyr*), in the northeast of the sheet, are extensions of major dykes on KURNALPI (Williams, 1970). These, along with the Binneringie and Jimberlana dykes, have positive magnetic anomalies and trend 075°. By contrast, the three prominent dykes between Randalls Dyke and Binneringie Dyke, have negative magnetic anomalies and trend 085° (Fig. 4). On KURNALPI, these different magnetic characters were interpreted by Williams (1970) to be the result of different ages of intrusion. Northwest-trending magnetic anomalies occur in southwest WIDGIEMOOLTHA which probably reflect subsurface mafic dykes, similar to the northwest-trending dykes on KURNALPI (Williams, 1970). Major linear negative anomalies, trending 045° and 020–030°, in central and northeastern WIDGIEMOOLTHA may also indicate unexposed mafic dykes.

Rb–Sr isotope analysis of the Celebration and Binneringie dykes (Turek, 1966) and Sm–Nd isotope investigation of the Jimberlana Dyke (I.R. Fletcher, 1985, pers. comm.) indicate an age of 2400 Ma for these mafic–ultramafic dykes.

The eastern part of the Jimberlana Dyke on WIDGIEMOOLTHA is undeformed, but swings from 080° in the south, near Norseman, to 060° near the pronounced 040° trend of the Fraser Complex in southeastern WIDGIEMOOLTHA. It appears that the orientation of the eastern end of the Jimberlana Dyke was controlled by pre-existing deep fractures. This perhaps suggests that the Albany–Fraser Orogen was tectonically active well before the younger metamorphic events dated at 1800–1100 Ma.

Woodline beds (*Puw*)

The Woodline beds are a sequence of mildly deformed and metamorphosed, shallow-water sedimentary rocks that rest unconformably on Archaean greenstones and granitoids (Sofoulis and Brock, 1962). They outcrop in the eastern half of WIDGIEMOOLTHA and strike northeast. In the south, a 70 m thick sequence of quartzite forms prominent hills with steep scree slopes. Sofoulis and Brock (1962) estimated the total thickness of the Woodline beds to be 200 m.

The upper part of the sequence comprises grey and white quartzite with trough cross-bedding and ripple marks. Poorly preserved, silicified pseudomorphs of gypsum crystals, in the highest parts of the sequence, suggest an evaporitic environment. The quartzite contains sedimentary breccia horizons (<1 m thick), pebbly sandstone, and thin silicified shale beds. The breccia consists of angular siliceous fragments (up to 5 cm across) in a siliceous sandy matrix. A pressure solution cleavage in the quartzite strikes 060°, parallel to the axis of a major fold of the Woodline beds. Weathered feldspathic material below the quartzite is probably derived from aplitic dykes.

The sequence beneath the quartzite includes red, grey, and black slate, and pelitic schist, together with minor quartzite containing thin units derived from pebbly sandstone. Basal silicified conglomerate and metasandstone lie unconformably on weathered, deformed Archaean schist, adjacent to a small lake 5 km southeast of Junction Lake. The metasandstone is thickly trough cross-bedded and dips moderately to steeply to the northwest. Clasts in this silicified rock were derived from vein quartz, fine-grained granitoid, and chert.

A low-energy aqueous environment is indicated by the metamorphosed mudstone and shale; shallow-marine or fluvial conditions were responsible for the coarse sandstone units. There appears to be an overall coarsening of the sequence towards the top.

The Woodline beds are Proterozoic in age (1620 ± 100 Ma, Turek, 1966). They are unconformable on the Archaean granitoid–greenstone terrain, and granitoid clasts occur in the basal conglomerate. The beds have been deformed and occupy an open syncline. The deformation is possibly related to deformation in the Fraser Range, 45 km to the east, where tectonic events dated at 1800–1100 Ma have been recorded (Myers, 1985).

PALAEOZOIC GEOLOGY

Poorly lithified, flat-lying, quartz sandstone, siltstone, and feldspathic grit (*Ps*) outcrop beneath laterite in breakaways on the western side of two small saline lakes in eastern WIDGIEMOOLTHA, and were described by Sofoulis and Brock (1962). These rocks most closely resemble those of the Paterson Formation (Lowry and others, 1972; Sofoulis, 1966, 'Wilkinson Range Beds') which contains glacigene and lacustrine deposits and has been assigned a Permian age from work in the Officer Basin (Lowry and others, 1972). Sofoulis (1966) previously considered them to be of Upper Jurassic–Lower Cretaceous age on the basis of palynology of the upper part of the sequence. However, this palynological work was pursued further, and the faunas quoted are non specific (J. Backhouse, 1985, pers. comm.).

CAINOZOIC GEOLOGY

Early Tertiary rocks, Eundynie Group (*Tes*)

Distribution

A variety of early Tertiary sedimentary rocks were extensively deposited in palaeodrainage systems now defined by the major lake systems and adjacent areas (Bunting and others, 1974). On a regional scale, the lakes outline a large pre-Eocene drainage system that flowed to the north, and then westward, across WIDGIEMOOLTHA (Fig. 5). Early Tertiary sedimentary rocks accumulated in broad valleys, in which lacustrine and fluvial sedimentary rocks are overlain by marine deposits which include bioclastic calcarenite and spongolitic siltstone. Only the upper parts of the sequence are exposed, in low cliffs and on lake floors, where later Cainozoic scarp retreat has dissected the early Tertiary rocks.

Lithology

Most outcropping rocks are quartz-rich siltstone and sandstone. They are generally strongly iron-stained, and overlain by laterite. Sponge spicules are abundant at many localities and limestones (shell beds and coral-rich calcarenites) outcrop in a few places. Fossils from this upper marine sequence include foraminifera, bryozoans, corals, bivalves, and sponge spicules (Table 1).

The lower fluvio-lacustrine sequence appears to be thicker in the southern part of WIDGIEMOOLTHA. Recent exploration drilling, for lignite and oil shale, indicated that this lower sequence consists of yellow, grey, and black clay, siltstone, lignite, and bituminous clay. The carbonaceous units reach a maximum average thickness of 20 m.

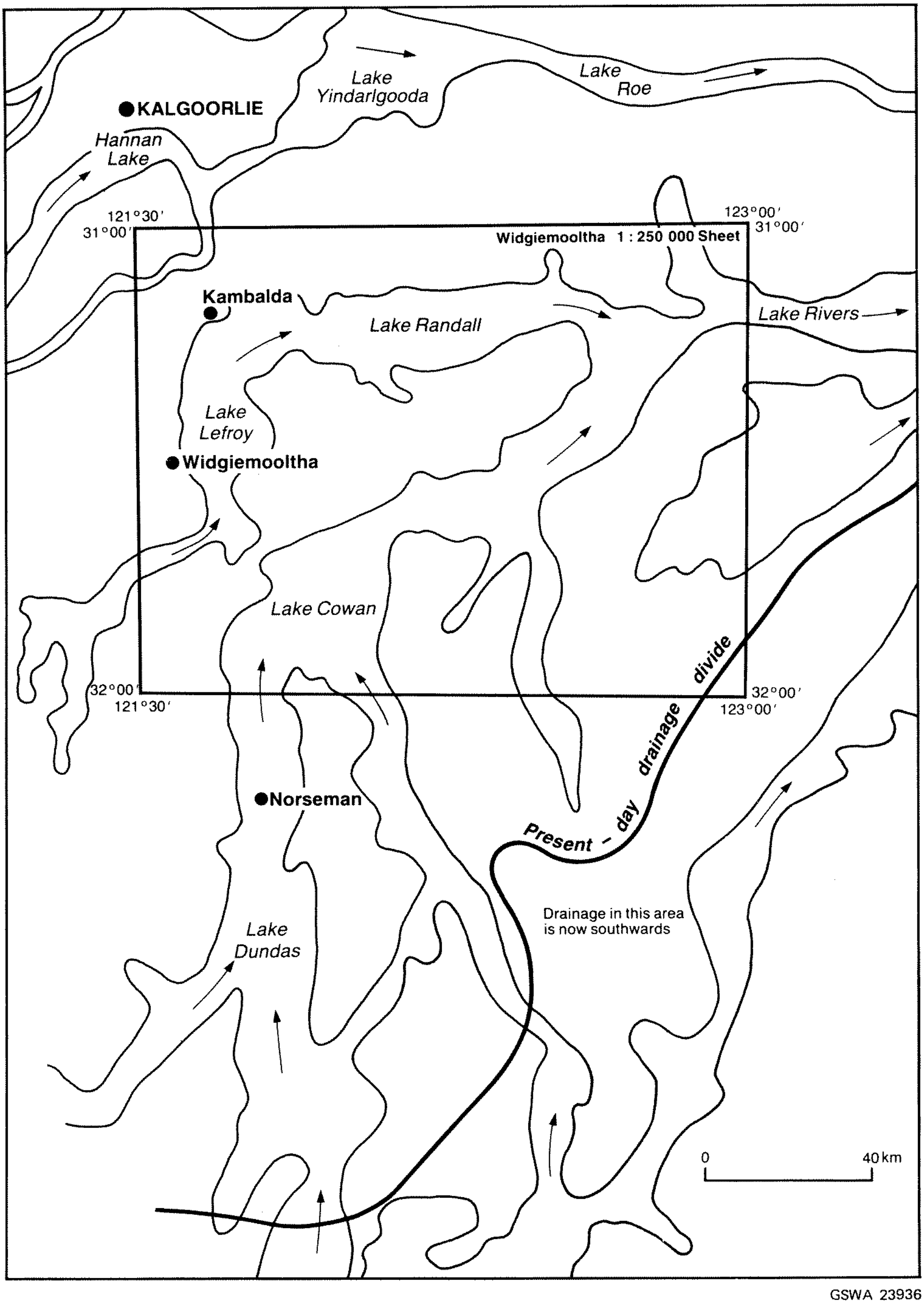

Figure 5. Pre-Eocene drainage system in the Kambalda–Norseman region

Drilling confirmed that the early Tertiary sedimentary rocks are essentially flat-lying, and were deposited in a valley system. There are rapid facies changes at the margins of valleys and some quite steep primary dips adjacent to basement rocks.

Age and stratigraphic relations

An Upper Eocene age, based on foraminifera, has been determined for these rocks. They are part of the Eundynie Group (Cockbain, 1968a). The three formations that make up the group (Norseman Limestone, Cowan Dolomite, and Princess Royal Spongolite) are, at least in part, laterally equivalent (Cockbain, 1968a). Cockbain (1968b) correlated these marine units, particularly the Princess Royal Spongolite, with the Pallinup Siltstone of the Plantagenet Group in the southwest of Western Australia, and the Toolina Limestone in the Eucla Basin.

Recent drilling shows that the Eundynie Group also contains a lower, predominantly lacustrine unit of clay and siltstone. This is probably equivalent to the Werillup Formation of the Plantagenet Group and has an Upper Eocene age (Fig. 6). The early Tertiary rocks are unconformable on the Archaean greenstones, and most are capped by laterite.

Thickness

The various units show extreme variations in thickness, but the maximum thickness of the Eundynie Group on WIDGIEMOOLTHA, recorded by drilling, is less than 100 m. The limestone unit is generally less than 10 m thick and is not always present.

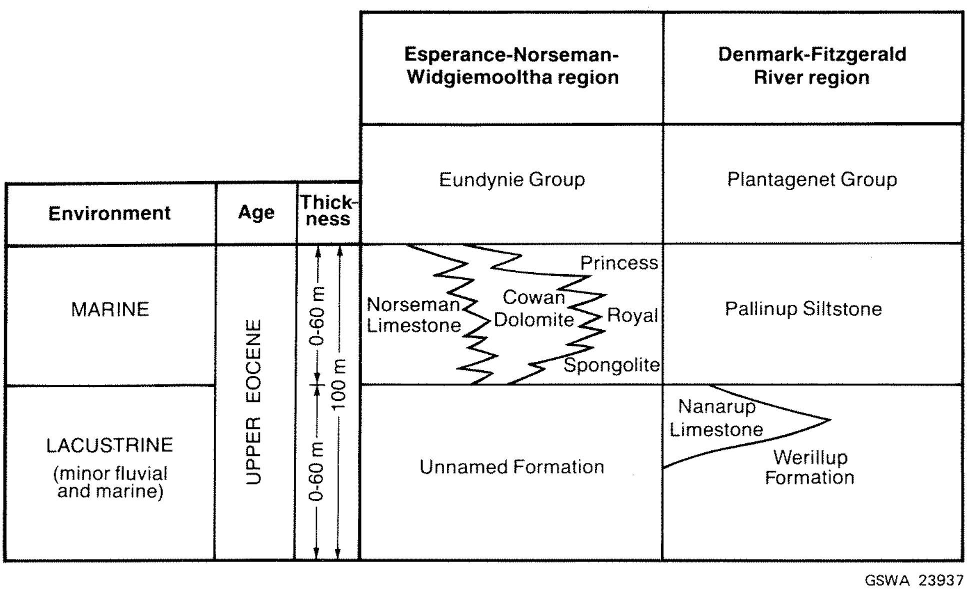

Figure 6. Diagrammatic summary of the stratigraphy and environment of Early Tertiary sedimentary rocks in the southwestern part of the Yilgarn Craton (after Cockbain 1986a,b)

Environment of deposition

The lower sequence lithologies are consistent with deposition in a broad terrestrial valley that initially had a shallow gradient draining to the north then east (Fig. 5). Tilting towards the south shifted the drainage divide northwards to its present position. This tilting reduced the gradient of the north-flowing streams and caused them to pond. There are rapid facies changes which are consistent with lake deposits within a broad valley system. A relative rise in sea level was responsible for the change to a marine environment, and sedimentation being restricted to low-lying areas of the pre-existing broad valley system.

Laterite, colluvium, alluvium, and playa-lake deposits

Laterite (*Czl*) is widespread and outcrops at various levels, from high on the watershed, to low country adjacent to lakes. The undulating nature of this now dissected surface is attributed to lateritization of an undulating Tertiary land surface (Sofoulis, 1966).

Pisolitic, blocky, and massive ferruginous duricrusts developed on deeply weathered rocks, including flat-lying early Tertiary sandstones. Calcareous and siliceous types are less common, but also widely distributed. Sofoulis (1966) noted that calcareous duricrusts with magnesite cement are generally associated with deeply weathered mafic rocks.

Semi-consolidated alluvial-fan deposits (*Czf*) outcrop in two areas on the western shore of Lake Lefroy, north of Widgiemooltha. The largest is south of Wanda Wanda Creek, and mostly north of Muldolia Creek. A separate, smaller fan is located further north, 8 km south of Kambalda. The best outcrops are on the lake shore and in some stream channels. They consist of angular, coarse quartz grains in an iron oxide and silica cement, and are highly porous. This unit is observed to have a maximum thickness of 2 m, and is covered by surficial material inland from Lake Lefroy. The broad distribution of the unit is based on topography and an obvious air-photo pattern. The fan deposit is lithologically similar to some of the early Tertiary immature quartz sandstones, but, because it lacks the lateritization common to rocks of Tertiary age, is considered to be younger. A lack of fine-grained material diminishes the possibility of finding fossils.

Surficial deposits (*Czc*) have developed on all rock types from the breakdown of bedrock, sheet wash, and colluvium near rock outcrops. Most of WIDGIEMOOLTHA is covered by this material along with lake deposits and associated dunes. Soils are generally sandy and contain lateritic fragments. In many areas the nature of the underlying rock has been assessed from the rock fragments in the soil, the air-photo patterns and textures, and in some cases exploration drilling. These areas are distinguished on the map by a symbol such as $\frac{Czc}{Ag}$, which indicates granitoid covered by surficial deposits.

Quaternary alluvium (*Qa*) occurs along gently sloping creeks where stream channels are poorly defined. Degradation has been restricted to the upper reaches and breakaways, and only a small amount of sediment has reached the lake shorelines (during severe thunderstorms), and formed deltas. Wide areas of alluvium (up to 3 km across) were also deposited adjacent to streams which drain into Lake Lefroy from the north. This is the result of occasional unusually heavy rain.

The Quaternary deposits are unconsolidated and poorly sorted, and range from clay to pebble size. Sections through the alluvium can be seen in steep-sided gullies, up to 3 m deep, where creeks have cut into flood-plain deposits.

Extensive playa-lake systems, dominated by Lake Lefroy and Lake Cowan, contain saline and gypsiferous clay and silt (*Czts*) up to 10 m thick. They overlie crystalline Archaean basement, or, up to 100 m of upper Eocene sedimentary rocks. The floors of some lakes extensively expose deeply weathered crystalline basement. However, when most lakes are dry, the surface is covered by brilliant-white salt (left by evaporation), a mineral resource that has been exploited on Lake Lefroy.

The margins of the playa lakes (particularly the eastern sides) contain dune deposits (*Cztd*) of unconsolidated quartz sand and gypsum. The dunes appear to be relatively stable. Most are covered by sparse low vegetation (including spinifex) and there are a few eucalypts on those dunes which are adjacent to wooded areas. Alluvial flats and small claypans are scattered between the dunes.

ECONOMIC GEOLOGY

WIDGIEMOOLTHA forms part of the Mineral Fields of East Coolgardie, Northeast Coolgardie, Coolgardie, and Dundas, where gold and nickel mining are important. Some freehold areas on WIDGIEMOOLTHA include mineral rights. These are East Location 48, 50 and 51, wholly on the sheet, and 45 and 53 partly on the sheet. Production information from these freehold areas is incomplete.

Nickel

Gold and base-metal exploration by Western Mining Exploration in 1964 led to the commencement of nickel mining in 1967 at the Silver Lake Shaft at Kambalda (Fig. 2). The associated nickel-exploration boom led to further discoveries in the Eastern Goldfields (Marston, 1985), many of them on WIDGIEMOOLTHA. The Kambalda Nickel Operation supports the town of Kambalda, and in 1984 produced 48 602 tonnes of nickel (over 5% of world production). Mine production for WIDGIEMOOLTHA is listed in Table 3.

Komatiite-associated deposits

All of the mines, and the majority of nickel mineralization on WIDGIEMOOLTHA, are associated with komatiite and have been classified (Marston, 1984) as volcanic peridotite-associated deposits.

The nickel sulphides are concentrated at or near the base of thick metakomatiite flows. Thin interflow sulphide-rich metasedimentary rocks are common, except immediately above mineralized parts of ultramafic flows. Marston (1984) describes a typical mineralized flow as having a basal zone of granular olivine and interstitial pyroxene, nickel and iron sulphides, iron oxides, and glass. This layer is overlain by a thin zone of relic spinifex-textured olivine and pyroxene with glass (now metamorphosed to antigorite, chlorite, tremolite, talc, magnesite, dolomite, and opaque minerals). About 90% of the mineralization of these komatiite flows is at the base, concentrated in depressions which may be channels in the underlying flow, formed by the erosive action of overlying flows. This thin, discontinuous, massive-sulphide zone is overlain by

TABLE 3. MINE PRODUCTION OF NICKEL CONCENTRATE FROM KAMBALDA (tonnes)

Year	*Kambalda–St Ives Group*	*Redross*	*Spargoville (location 3, on Boorabbin map sheet)*	*Carnilya East (Carnilya Hill)*	*Mount Edwards*	*Wannaway*
1967	296					
1968	5 483					
1969	7 876					
1970	29 686					
1971	32 552					
1972	26 896	28				
1973	33 861	7				
1974	41 358	1 713				
1975	36 857	2 890	1 195			
1976	33 784	4 080	1 980			
1977	36 811	3 226	2 865			
1978	40 242	1 198(c)	1 802			
1979	42 718		2 059			
1980	35 997(a)		2 676(d)	889		
1981	29 414			3 970		
1982	36 325(b)			3 046	547	
1983	40 647			3 470	3 614	
1984	40 657			3 641	3 955	349
1985	35 925			3 563	1 905	1 406
1986	31 621			2 901	562	269
Total	**619 006**	**13 142**	**12 577**	**21 480**	**10 583**	**2 024**

NOTES: (a) Possibly includes production from Carnilya in 1980.

(b) Part of production from Mount Edwards probably included in 1982.

(c) Operations closed in 1978.

(d) Operations closed in 1980.

thicker, more continuous, disseminated sulphides. Some massive and brecciated ores have been tectonically disrupted, and contain complex troughs and embayments in the footwall (Marston, 1984; Gresham and Loftus-Hills, 1981). The nickel content of the sulphide fraction ranges from 5 to 23%, with an associated increase in Ni:Cu ratio from 10 to 16.

Copper, cobalt, platinum group metals, and gold are important by-products of nickel production at Kambalda. Annual production is: 1000–3000 t Cu; 150–200 t Co; 200–300 kg Pd and Ag; and 100–250 kg Pt and Au.

The nickel-sulphide deposits on WIDGIEMOOLTHA are the major occurrences of this type in the Norseman–Wiluna zone of the Eastern Goldfields Province. They are restricted to the most extensive exposures of greenstones in western WIDGIEMOOLTHA. In a broad stratigraphic sense, they are associated with the thickest sequences of mafic–ultramafic rocks, which are overlain by metamorphosed felsic volcanics and metasedimentary rocks. Structures are generally steeply dipping and strike north-northwest, and the ore zones are deformed.

Gresham and Loftus-Hills (1981) considered that the ore originated as a sulphide melt, either simultaneously or sequentially with komatiite lava extrusion from linear fissures, and in a subaqueous environment. The fissures are thought to be associated with rifts in which thick nickel-bearing komatiite was extruded at the rift margins.

Vein arsenical deposits

Vein arsenical deposits (Marston, 1984) form a second type of nickel mineralization on WIDGIEMOOLTHA, and an example occurs at Mount Martin. It consists of disseminated veinlets of quartz, carbonate, sulphide, arsenide, and gold in metasedimentary rocks near a contact with carbonatized ultramafic rocks. Marston (1984) considered this deposit to be of late metamorphic–hydrothermal origin.

Nickel exploration is continuing, particularly at Kambalda, Carnilya, around Widgiemooltha, and southwards to Redross.

Gold

Gold production from WIDGIEMOOLTHA is presented in Table 4. The majority is from Kambalda Nickel Operation, which, in addition to nickel, produced 7876 kg of gold between 1979 and mid-1984. This included ore mined both within and outside WIDGIEMOOLTHA. The Kambalda Nickel Operation, in 1986, milled about 1.3 Mt of gold ore, and produced over 5 t of gold

The first gold mines in the area were located on high-grade gold-bearing quartz veins. In some cases these high grades were partly due to supergene enrichment. The mines were quite shallow and restricted to exploiting material above the water table. Vein-deposit gold occurs in all rock types which include: metasedimentary rocks at Mount Martin and Mount Belches; felsic schists at Mount Monger; metamorphosed felsic intrusives at Hampton–Boulder; and mafic rocks at White Hope. Most of the gold mineralization is associated with carbonate-altered sheared rock and quartz veins.

The major mining centre is Kambalda, where today ore from nine mines is processed (although two of the larger mines, Great Boulder and Sand King, lie to the north on KALGOORLIE). Mines which are currently operating and sending ore to Kambalda are: Victory (underground and heap leaching, the open-pit operation having been completed); Defiance (open pit and underground producing over 1500 kg Au p.a.); Mount Mine — 4 km south of Widgiemooltha; Cave Rocks — 10 km west of Kambalda; Orchin; and small amounts of ore from Ives Reward, Fisher and Delta Island. The Hunt gold mine is no longer a regular producer of gold ore. A small amount of gold is also won by the gravity method from the nickel ore, but most of the gold associated with nickel production is contained in the nickel matte (along with Ag, Pt, and Pd) and is not extracted at Kambalda.

The gold mineralization at Hunt and Defiance is associated with disseminated pyrite in alteration zones adjacent to quartz veins in mafic rocks. It is similar to that at Mount Charlotte, Kalgoorlie. At Hunt, the mineralization occurs in a shear zone within the Kambalda Footwall Basalt (Phillips and Groves, 1982; Groves and others, 1982). Coarse quartz vein and coarse gold (of specimen grade) occurs at the contact of the altered sheared zone with the unsheared overlying nickel-bearing ultramafic rocks. The mineralization at Mount, Cave Rocks, Paris, White Hope and Higginsville is also hosted by sheared mafic rocks.

TABLE 4. TOTAL GOLD PRODUCTION FROM WIDGIEMOOLTHA (TO DECEMBER 1986)

District	*Mining Centre*	*Alluvial and dollied (kg)*	*Ore treated (tonnes)*	*Gold (kg)*	*Total gold (kg)*	*Remarks*
East Coolgardie	Cutters Luck	21.7	1 013	19.4	41.1	Geological Survey alluvial gold in 1977
	Feysville	18.0	3 834	45.0	62.9	Includes Celebration, Bellevue, and Fox's Find on Kurnalpi Sheet. 8 kg mined in 1974–75
	Hampton Plains	154.6	621 851	4 132.9	4 287.5	See also Hampton Plain Coolgardie District below. Includes production from Inalienable Freehold land for which gold production is incomplete. Includes 36 kg from Golden Hope and 65 kg from White Hope in 1982.
	Wombola	112.1	249 206	5 816.5	5 928.7	Production figures for leases on Widgiemooltha based on data in Hickman (1986)
	'Mount Monger'				4 715	
	'Wombola, Mount Monger and Hogan's Find'				1 327	
Bulong	(Mount Monger	92.9	1 846	48.7	141.6)	Included above
	Randalls	2.9	41 124	388.5	391.4	Includes 0.5 kg in 1983 (probably tailings at Karnilbinia)
Dundas	Peninsula	1.0	14 338	227.2	228.2	Recent production from 1979, include 8.5 kg in 1981– (probably Peninsula)
Kurnalpi	Karonie		1 517	13.0	13.0	
Coolgardie	Cave Rocks	1.6	15 013	111.6	113.2	Recent production included in Kambalda
	Eundynie	8.0	33 102	530.8	538.8	0.4 kg in 1980
	Hampton Plains	21.7	314 641	4 875.1	4 896.8	See Hampton Plains, East Coolgardie. Includes Barbara Surprise on the Kalgoorlie sheet, 4485 kg

TABLE 4. Continued

District	Mining Centre	Alluvial and dollied (kg)	Ore treated (tonnes)	Gold (kg)	Total gold (kg)	Remarks
	Higginsville	32.1	128 804	996.8	1 029.0	Significant recent production 1972–80, and 61 kg 1985–86
	Kambalda	54.9	3 416 408	15 905.2	15 960.2	Includes production from Hunt, Victory and Defiance (1984–2890 kg with over 200 kg contained in Ni matte. Replaces production previously recorded under Red Hill and St Ives
	Paris	0.2	72 709	818.3	818.5	1983–6 production approximately 45 kg
	Red Hill	52.1	42 973	1 001.4	1 053.5	Production in recent years under Kambalda
	St Ives	42.8	44 213	549.6	592.4	Production in recent years. Victory-Defiance under Kambalda
	Wannaway	7.5	3 918	88.6	96.1	
	Widgiemooltha	62.0	59 952	752.9	814.7	Main production in recent years 1979–80 includes 27 kg in 1984

Gold deposits also occur in metasedimentary rocks: at Mount Belches in banded iron-formation (Groves and others, 1982); at Mount Martin in quartz-sulphide veins in a narrow unit of phyllite close to ultramafic schist; and at Peninsular within quartz veins in sheared metasedimentary rocks adjacent to ultramafic rocks. Gold in metasedimentary rocks at Victory is in a sulphidic slate containing 5–80% pyrite. At the surface, it is a silicified ferruginous slate that correlates with a slate marker at Kambalda, and with the Kapai Slate at Kalgoorlie. At Victory, gold is also present in shear zones, and is associated with disseminated pyrite in adjacent mafic schist and altered felsic-porphyry dykes.

Felsic rocks contain gold mineralization in the Boulder–Lefroy Fault on northeastern WIDGIEMOOLTHA. The mineralization between Celebration and Golden Hope involves an albitized felsic porphyry. At Hampton–Boulder (New Celebration) and Jubilee, the gold is associated with fine stringers of pyrite in a close-spaced, complex fracture system. The highest gold grades are in quartz–pyrite veins on the contact with the mafic–ultramafic schist. Sheared felsic rocks with gold-bearing quartz veins occur in the Mount Monger area at Haoma-Daisy (Hickman, 1986).

Chlorite–carbonate schist, without quartz veins, yielded significant gold at Great Hope mine in the Mount Monger area (Hickman, 1986).

Small amounts of gold are currently being recovered by heap leaching of tailings from previous gold mining. This method is also used to extract gold from low-grade ore from open-pit operations where the ore is oxidized and weathered and does not have to be crushed.

Open-pit gold mining of large low-grade deposits, often located at the site of previous quartz-vein mines, is widespread on WIDGIEMOOLTHA. The ore is deeply weathered, and sulphides are oxidized; mining can take place to a depth of about 60 m with minimal blasting and crushing. The gold is readily extracted by wet-gravity methods followed by carbon-in-pulp treatment. Small deposits, and deposits with low-grades, can be mined profitably provided the infrastructure is available.

At present there is active gold exploration, and several low-grade surface deposits are likely to be mined in the next few years. Extension to underground mining will depend on results from deep drilling, primarily in areas of low-grade surface ore. The possibility of alluvial concentrations of gold in sedimentary rocks on the Archaean basement has attracted some exploration interest.

Tin and tantalum

Cassiterite and tantalite have been mined from alluvium and colluvium in the Bald Hill region, northeast of Binneringie homestead. They are derived from pegmatite veins and associated greisen in metasedimentary rocks. A total of 1.86 t of tin concentrate has been produced at a grade of 62% Sn (Blockley, 1980). Limited shallow mining of pegmatite veins, involving blasting and hand picking the ore, was carried out in 1981. In addition to tantalite and cassiterite, beryl and some lithium minerals may also be potentially valuable components of the pegmatites.

Copper

Copper is produced as a by-product of nickel ore from chalcopyrite concentrates. Up to 1980, 16 421 t of copper had been produced, and represented most of the copper produced in Western Australia (Marston, 1984).

In the past, copper was also produced as a by-product of gold mining at Higginsville (7 t of copper at a grade of 9.59%) and the Paris mine (191.5 t of copper) (Marston, 1979). Further exploration at Higginsville has so far failed to find a major extension of the known copper mineralization.

Copper minerals also occur at Mount Monger (Hickman, 1986), St Ives (Sofoulis, 1966), and Hinamoa.

Some minor disseminated chalcopyrite was found in garnet amphibolite of the Albany–Fraser Orogen during nickel exploration in the 1970s.

Salt

Salt dumps around the southwestern shore of Lake Lefroy are indications of former salt extraction operations. Major production from evaporation ponds on Lake Lefroy, north of Lefroy Peninsula, ceased in 1982. The total amount shipped was 1 243 898 t.

Talc

Talc, produced from ultramafic rocks at the Lass O'Gowrie mine near Mount Monger homestead, totalled 1367 t.

Tungsten

A total of 19.5 t of scheelite concentrate has been recovered as a by-product of gold in the Higginsville area (Sofoulis, 1966).

Prase

Prase has been mined in an area just west of WIDGIEMOOLTHA, 7 km south of Spargoville (Connolly, 1966). Another occurrence is in weathered material above the Jimberlana Dyke in southeast WIDGIEMOOLTHA.

Uranium

Exploration for uranium has been undertaken in the Tertiary sedimentary rocks associated with the lake systems in northeastern WIDGIEMOOLTHA, and in the Woodline beds.

Opals

Some high-grade opals were recovered on north WIDGIEMOOLTHA, east of Cowarna Downs, but efforts to establish a mining operation in the 1970s failed.

Molybdenum

Molybdenite in quartz veins on the granite–metasedimentary rock contact, northeast of Binneringie homestead, has been investigated by drilling, but substantial mineralization has not been located.

Limestone

Tertiary limestone has been investigated near Blue Dam, 13 km southeast of Binneringie homestead, for use as a flux in nickel processing.

Gypsum

Gypsum is an abundant component of dunes associated with the playa lakes, particularly on the southern and eastern margins of the lakes. It has been quarried from the southern part of Lake Cowan on NORSEMAN. The road and rail link to the port of Esperance is an important factor in the economic viability of these bulk, low-value deposits.

Lignite and petroleum

A significant level of exploration has taken place for lignite and oil shale in the lower part of the Tertiary succession, broadly associated with the playa-lake systems mainly on southern WIDGIEMOOLTHA. Over 100 shallow holes have been drilled, and total assumed reserves exceed 1000 Mt of oil shale. Values range from 60 to 200 L oil/tonne for the shale. Moisture and salt content are high, and net energy values for the largest reserves are around 6 Mj/kg. These deposits, together with similar deposits to the south in the Esperance–Norseman region, represent a significant potential power source. However, their heating value is much lower than Collie coal which has a net energy level of about 20 Mj/kg.

Water resources

There are no permanent streams on WIDGIEMOOLTHA; dams rely on rain from thunderstorms for their supply. Hogan's Lagoon is the only significant natural fresh-water lake and has rapid seasonal fluctuations in water level. The towns of Kambalda and Widgiemooltha, and the large-scale mineral-processing operations in the region, are supplied with water by pipeline from Mundaring Reservoir near Perth, via Coolgardie.

Groundwater is generally very saline, particularly near playa lakes. The best quality water occurs in shallow aquifers in higher country, in small catchments in areas of granitoid. Some saline groundwater is utilized in the treatment of gold ores, particularly in the carbon-in-pulp process.

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WIDGIEMOOLTHA

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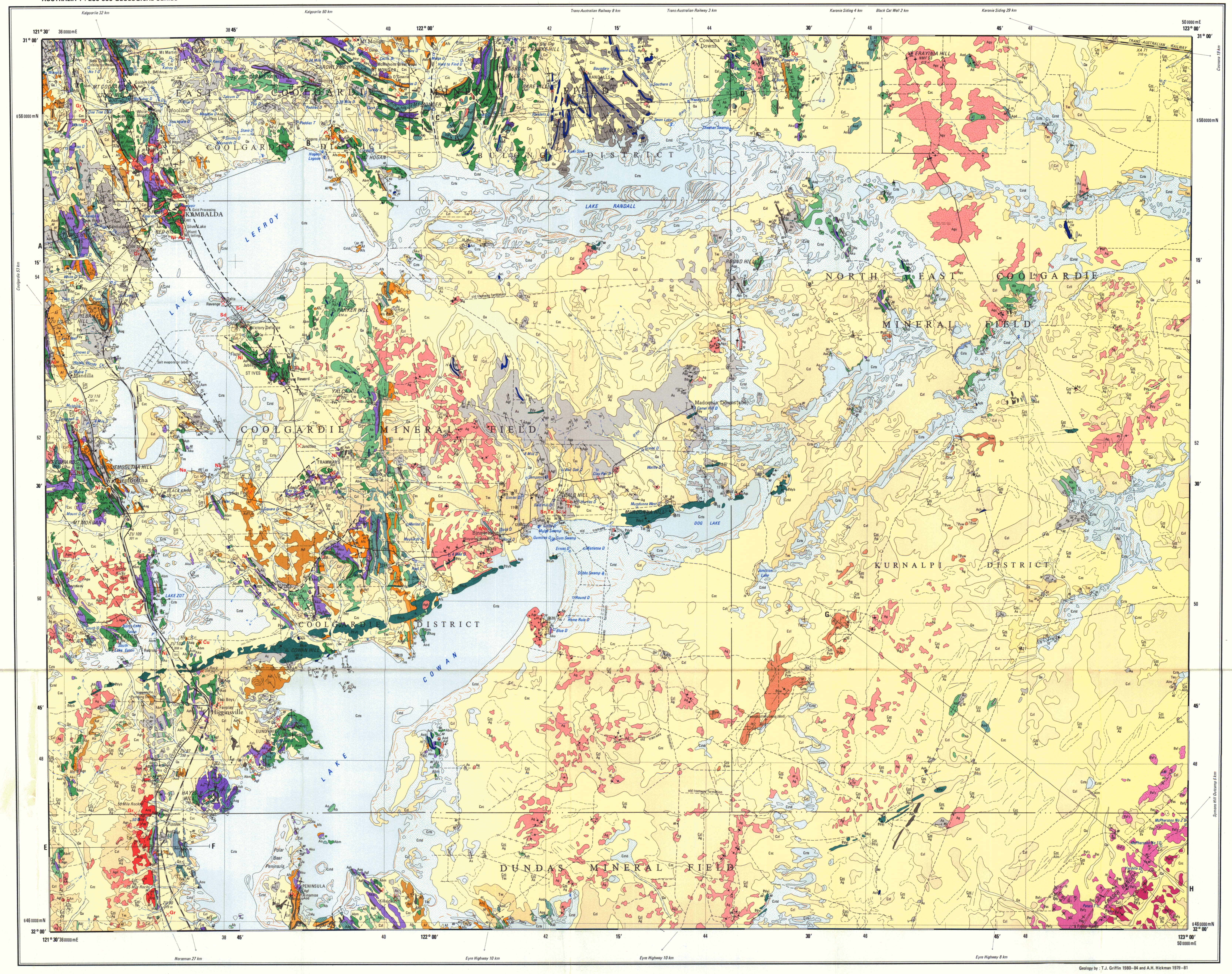
GEOLOGICAL SURVEY OF WESTERN AUSTRALIA

SHEET SH 51-14



Geology by : T.J. Griffin 1980–84 and A.H. Hickman 1979–81

SYMBOLS

Geological boundary
Interpreted geological boundary
Fault, inferred or concealed
Shear zone
Fold
- anticline
- syncline
- overturned anticline
- overturned syncline
- plunge, plunge of minor fold
- M vergence

Bedding
- inclined
- vertical
- horizontal

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

Cleavage
- inclined
- vertical
- strike coincident with bedding
- with lineation

Foliation, metamorphic
- inclined
- vertical

Foliation, igneous
- inclined
- vertical

Joint
- inclined
- vertical

Air photo lineament
- concealed mafic dyke
- lithological or structural trend

Fossil locality
- macrofossil
- silicified wood fossil
- trace fossil

Mineral field boundary
Mineral field district boundary
Highway with national route marker — 94
Formed road
Track (many exploration and logging tracks not shown)
Railway, with siding
Old tramway formation
Powerline
Townsite gazetted
- pop. 1 000 – 10 000 — KAMBALDA
- pop. less than 1 000 — Widgiemooltha

Homestead — Mt Monger
Building
Locality — Kambalda West
Landing ground
Microwave repeater site — Pioneer
Horizontal control; major, minor
Vertical control, height accurate — ZU 120 344 m
Breakaway
Sand dunes
Abandoned — (abd)

Watercourse, ephemeral
Pipeline — P
Playa lake, fresh-brackish
Dam — D
Tank — T

Mining locality — ST IVES
Mine or opencut (gold unless otherwise indicated) — Fairplay
Mine, abandoned
Alluvial workings abandoned
Tailings treatment plant — T
Battery abandoned
Mineral occurrence
- Copper — Cu
- Gold — Au
- Molybdenum — Mo
- Nickel — Ni
- Opal — Op
- Salt — Na
- Tantalum — Ta
- Tin — Sn

Pit
- Gravel — Gr
- Sand — Sd

REFERENCE

CAINOZOIC

QUATERNARY

Qa — Alluvium

Czts, Cztd
- Czts — Evaporite, interbedded with clay and sand
- Cztd — Quartz sand and gypsum dune deposits

Czc, Czf, Czl
- Czc — Colluvium
- Czf — Semiconsolidated ferruginous quartz sandstone
- Czl — Laterite

TERTIARY

Tes — **Eundynie Group**: sandstone, siltstone, and mudstone; including spongolitic, calcareous and bituminous varieties

PALAEOZOIC

? PERMIAN

Ps — **? PATERSON FORMATION** : quartz sandstone and siltstone

PROTEROZOIC

Puw — **WOODLINE BEDS** : arenaceous and argillaceous metasedimentary rocks, including silicified evaporite

Pa, Pas, Paf1, Paf2, Paf4, Paf5, Pag
- Pa — **ALBANY–FRASER OROGEN** : granulite and amphibolite facies rocks, including metagabbro, metasedimentary rock, metagranitoid rock and gneiss
- Pas — Gneiss and metasedimentary rock
- Paf_1 — Garnet amphibolite (strongly magnetic)
- Paf_2 — Pyroxene granulite (weakly magnetic)
- Paf_4 — Pyroxene granulite (moderately magnetic)
- Paf_5 — Metagabbro
- (Paf_1–Paf_5: **FRASER COMPLEX**)
- Pag — Gneissic augen granitoid rock

Pdy — Mafic and ultramafic dykes : Pdyb – Binneringie Dyke; Pdyc – Celebration Dyke; Pdyj – Jimberlana Dyke; Pdyr – Randalls Dyke

ARCHAEAN

q — Quartz veins

Alm — Quartz muscovite schist (? deformed Ag)

Ag — Dykes : Ag, Agf, Ags, Agp as below

Ag, Agy, Agn, Agrh, Agw, Agf, Ags, Agp, Agh
- Ag — Granitoid rock
- Agy — **ERAYINIA GRANITOID COMPLEX** : foliated hornblende biotite monzogranite and porphyritic granodiorite with abundant small mafic xenoliths
- Agn — **PIONEER GRANITOID COMPLEX** : foliated porphyritic monzogranite and gneiss with pegmatite and quartz veins
- Agrh — **RED HILL GRANITOID COMPLEX** : syenogranite, monzogranite porphyry and granodiorite porphyry
- Agw — **WIDGIEMOOLTHA MONZOGRANITE** : foliated porphyritic monzogranite
- Agf — Monzogranite porphyry and granodiorite porphyry
- Ags — Porphyritic syenite
- Agp — Pegmatite
- Agh — Granitoid rock hornfelsed by the Binneringie Dyke

An, Ang
- An — Quartzo-feldspathic gneiss
- Ang — **FIFTY MILE TANK GNEISS** : quartzo-feldspathic gneiss and augen gneiss

As, Asm, Asf, Ash, Ach, Asw, Asb, Aci
- As — Pelitic and psammitic metasedimentary rocks with metaconglomerate, chert and metamorphosed felsic volcaniclastic rocks
- Asm — **MEROUGIL BEDS** : biotite-bearing metasedimentary rocks derived from pebbly sandstone, sandstone and siltstone
- Asf — Metamorphosed felsic volcaniclastic sedimentary rock and minor volcanic rocks
- Ash — Metamorphosed shale and slate
- Ach — Chert
- Asw — **MOUNT BELCHES BEDS** : biotite-bearing metasedimentary rock derived from turbidite
- Asb — Mafic schist interlayed with quartz-rich schist
- Aci — Metamorphosed banded iron-formation

Af — Metamorphosed felsic volcanic rock

Afs — Felsic schist

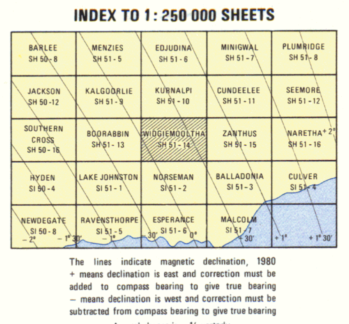
Ao, Aod, Aog, Aou
- Ao — Metamorphosed mafic and ultramafic intrusive rocks
- Aod — Metadolerite
- Aog — Metagabbro
- Aou — Metaperidotite and metapyroxenite

Ab, Abm, Abt
- Ab — Mafic schist, metabasalt, metadolerite and amphibolite
- Abm — Metamorphosed high-Mg basalt, with some pillows and variolitic textures
- Abt — **KAMBALDA FOOTWALL BASALT** : metamorphosed pillow basalt

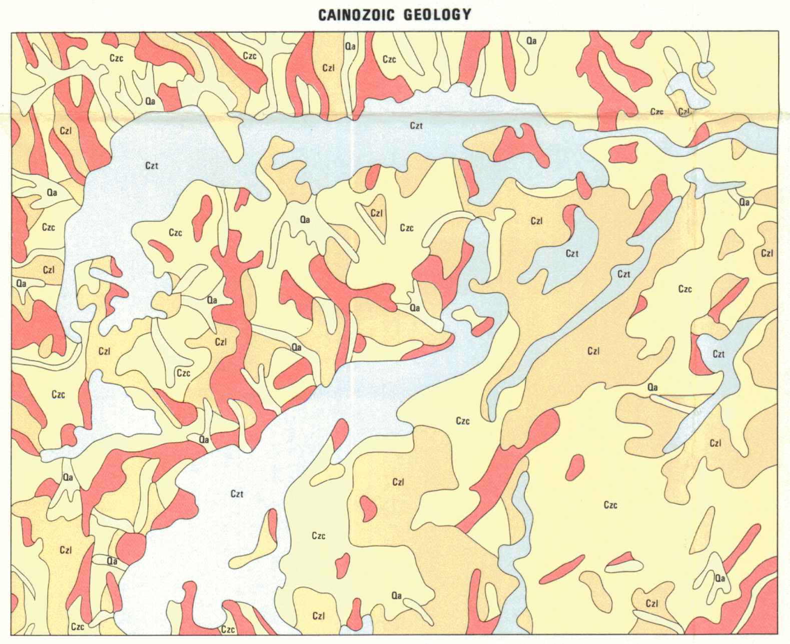
Aku — Metakomatiite

Au — Ultramafic schist

INDEX TO 1: 250 000 SHEETS



CAINOZOIC GEOLOGY



Qa — Alluvium
Czt — Playa deposit
Czc — Colluvium
Czl — Laterite
Rock and weathered rock

SCALE 1: 250 000

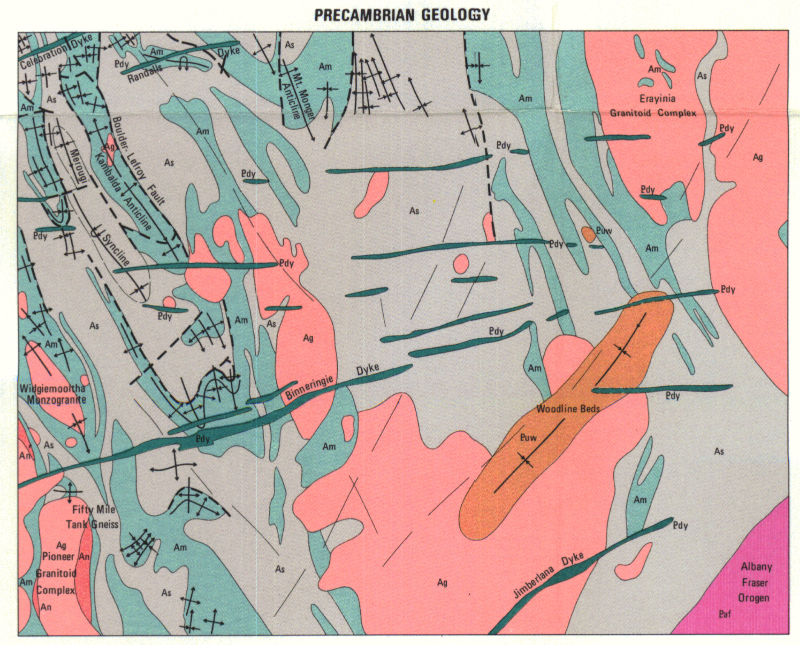
Metres — Kilometres

TRANSVERSE MERCATOR PROJECTION

ZONE 51 AUSTRALIAN MAP GRID

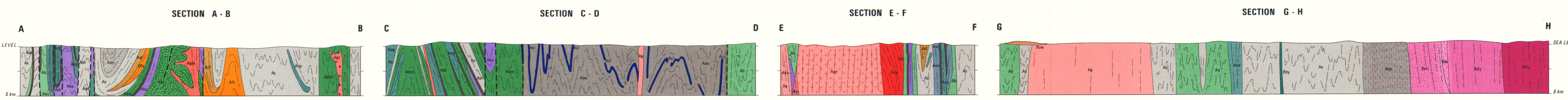
PRECAMBRIAN GEOLOGY

Mafic dyke
Woodline Beds
Albany Fraser Orogen
Granitoid rock
Gneiss
Metamorphosed igneous rock
Metasedimentary and metamorphosed felsic rock
Magnetic lineament



DIAGRAMMATIC SECTIONS

NATURAL SCALE



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