

**REPORT  
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# **GEOLOGY AND MINERALIZATION OF THE PALAEOPROTEROZOIC YERRIDA BASIN WESTERN AUSTRALIA**

**by F. Pirajno and N. G. Adamides**



**GEOLOGICAL SURVEY OF WESTERN AUSTRALIA  
DEPARTMENT OF MINERALS AND ENERGY**



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**Cover photograph:**

**Breakaway in a turbiditic arkose of the Doolgunna Formation, near the Goodin Find gold deposit.**

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## Digital data (in pocket)



Whole-rock geochemical analyses of Killara Formation rocks (killara.csv)

# Geology and mineralization of the Palaeoproterozoic Yerrida Basin, Western Australia

by

F. Pirajno and N. G. Adamides

## Abstract

The Palaeoproterozoic Yerrida Basin is part of the Capricorn Orogen, a zone of low- to high-grade metamorphic rocks, magmatic belts, and low-grade volcano-sedimentary basins that were formed as a result of the oblique collision between the Pilbara and Yilgarn Cratons at about 1.8 Ga. The Yerrida Basin was probably formed at approximately 2.2 Ga and was affected by the Capricorn Orogeny. The Yerrida Basin has a faulted contact with the Bryah Basin in the west (Goodin Fault) and the Marymia Inlier in the north, and is unconformably overlain by rocks of the Earraheedy Basin in the east. Rocks that have accumulated in the Yerrida Basin are assigned to the Yerrida Group (formerly part of the Glengarry Group).

The stratigraphy of the Yerrida Group is complicated by interdigitating relationships between the component units. The Yerrida Group is divided into the Windplain and Mooloogool Subgroups. The Windplain Subgroup contains the Juderina and Johnson Cairn Formations, which include siliciclastic rocks, evaporites, argillites, and locally turbidites. The rocks of the Windplain Subgroup were deposited in a shallow epicontinental sea, locally with sabkha environments. The Mooloogool Subgroup was deposited in a high-energy environment, probably in a widening rift structure, surrounded by uplifted Archaean rocks of the Marymia and Goodin Inliers. The Subgroup comprises four formations: the Doolgunna, Thaduna, Killara, and Maraloo Formations. The first two contain turbiditic rocks deposited in deepening rifts. The Killara Formation contains continental tholeiitic basalts that were erupted along northeasterly, easterly, and northwesterly trending structures, a few of which contain dolerite dykes. The Doolgunna, Thaduna, and Killara Formations interdigitate, suggesting that sedimentation and volcanism were contemporaneous. The end of volcanism is marked by the deposition of chert units (Bartle Member), and sedimentological, textural, and petrographic data suggest that they were formed in a playa lake environment, with hot springs. The final phase of rifting is represented by sulfidic shale and laminated siltstone of the Maraloo Formation, probably of lacustrine facies.

Known mineralization consists of shear zone-hosted copper deposits, quartz veins containing base metals, black shale-hosted barium, copper, platinum-group elements, and a large lead–carbonate deposit (Magellan) in the southeast. This lead deposit is present in the upper units of the Juderina Formation and the lower units of the Yelma Formation (Earraheedy Group), which are preserved as scattered outliers in the region.

The geodynamic evolution of the Yerrida Basin is interpreted as having commenced as a pull-apart opening related to sinistral strike-slip faulting. Subsequent to this opening, a rift phase occurred during which the continental tholeiitic lavas of the Killara Formation were erupted. The life of the Yerrida Basin concluded with the formation of an intracontinental lake and the deposition of lacustrine sediments.

**KEYWORDS:** Palaeoproterozoic, Bryah Basin, Yerrida Basin, Earraheedy Basin, evaporites, stromatolites, tholeiite, basalt, rift basin, copper, lead, palladium, barium, mineralization, tectonics.

## Introduction

In early 1994, fieldwork commenced on a project aimed at reappraising the geology and mineralization of the Palaeoproterozoic Glengarry Basin, as part of a program of new mapping initiatives by the Geological Survey of Western Australia (GSWA). The Glengarry Basin, as defined by Gee and Grey (1993), was the western part of the greater Palaeoproterozoic Nabberu Province, which in the east included the Earahedy Basin (Bunting et al., 1977; Hall and Goode, 1978; Gee, 1990). This project resulted in the recognition that the Glengarry Basin of Gee and Grey (1993) consists of three tectonic units: the Bryah, Padbury, and Yerrida Basins (Fig. 1; Plate 1). As a result, the volcano-sedimentary rocks of the Glengarry Group are now divided into the Bryah and Yerrida Groups (Fig. 2), characterized not only by different lithologies, but also by different regional structures, metamorphism, and mineral deposit types. Sediments and volcanic material that accumulated in the Yerrida Basin have been assigned to the Yerrida Group, which is discussed in detail below. The Yerrida Group is unconformably overlain by the Earahedy Group of the Earahedy Basin.

Work in the Yerrida Basin involved 1:25 000-scale mapping to produce 1:100 000 geological series map sheets. Geological mapping was carried out using colour aerial photographs, available from the Department of Land Administration (DOLA), and Landsat Thematic Mapper (TM) and magnetic images. Results of geological mapping were integrated with petrographic and geochemical studies. During this work a total of 648 rock or core samples were collected, of which 350 were made into thin and polished sections and 126 geochemically analysed. In addition, logging of 1000 m of diamond drillcore and visits to prospects and old mines enhanced the knowledge of the geology of the area. Most of the mapped areas were also included in a regional geochemical sampling program that covered the 1:250 000 *PEAK HILL*\* and *GLENGARRY* sheets (Subramanya et al., 1995; Crawford et al., 1996). Published geological maps at 1:100 000 scale and accompanying Explanatory Notes that include parts of the Yerrida Basin comprise *DOOLGUNNA* (Adamides, 1998), *GLENGARRY* (Pirajno et al., 1998a), *MOOLOOGUOL* (Pirajno et al., 1998b), *MOUNT BARTLE* (Dawes and Pirajno, 1998), *THADUNA* (Pirajno and Adamides, 1998), *CUNYU* (Adamides et al., 1999), *MARYMIA* (Bagas, 1998), *WILUNA* (Langford and Liu, 1997), and *MEREWETHER* (Ferdinando and Tetlaw, in prep.). The layout of these map sheets in relation to the Yerrida Basin and adjacent tectonic units is shown in Figure 1.

Interim accounts of the tectonic evolution of the Yerrida Basin and its structural and stratigraphic relations with the adjacent Bryah and Padbury Basins have been reported by Pirajno et al. (1995, 1996) and Occhipinti et al. (1997). Models of the tectonic evolution of these basins have been discussed by Pirajno (1996) and Pirajno et al. (1998c).

\* Capitalized names refer to standard 1:100 000 map sheets, unless otherwise indicated.

† In this section we use the terminology established by previous workers; thus Glengarry Group or Basin collectively refer to the Bryah, Padbury, and Yerrida Groups or Basins.

In this Report the geology, stratigraphy, volcanic geochemistry, and mineralization of the Yerrida Basin are discussed. The Report concludes with a model of the geodynamic evolution of the Yerrida Basin, based on the field, geochemical, petrographic, and geophysical data presented in this work.

## Previous investigations

The earliest account of the geology of the Yerrida Basin was that of Talbot (1920, 1928) who examined the physiography and regional geology of part of Western Australia between 1912 and 1914, over an area of 180 000 km<sup>2</sup>. The geology was broadly subdivided into areas of granite, greenstone, and younger sedimentary units. The Proterozoic sedimentary rocks between Wiluna and the Glengarry Range were collectively included in the Nullagine Beds, which Talbot extended south from Nullagine and the Throssell Range. Talbot (1920, 1928) also provided detailed geological descriptions of rock units in the various areas, supplemented by petrographic work by R. A. Farquharson.

Sofoulis and Mabbutt (1963) described the geology of the same region and first recognized the unconformity between the 'Nabberu Basin' and Archaean basement. They separated the Archaean metamorphic belts into a lower greenstone and an upper whitestone phase, whereas the Proterozoic succession was collectively included in the Nullagine system. Sofoulis and Mabbutt (1963) described the arenite outcrops in the area of Mount Alice, north of Wiluna, and concluded that the sediments were laid down in fairly shallow basins in the Archaean basement. The boundaries of Sofoulis and Mabbutt (1963) were extrapolated north by Horwitz (1966) on the 1:2 500 000 State geological map. Horwitz (1966) considered the rocks presently included in the Earahedy Group to be the oldest Proterozoic sedimentary rocks, with the Glengarry Group<sup>†</sup> being transgressive onto them, and equated with the Wyloo and Manganese Groups of the eastern Pilbara region. However, he correctly mapped the unconformity between the Bangemall Group rocks and the older units. The granite of the Goodin and Marymia Inliers was thought to intrude the Proterozoic sequence.

The interpretations of Sofoulis and Mabbutt (1963) remained on State geological maps until the work of MacLeod (1970), who produced the first geological map of the *PEAK HILL* 1:250 000 sheet. MacLeod (1970) speculated an Archaean age for the sedimentary units between the Goodin and Marymia Inliers. This was done on the basis of lithological and structural similarities to Yilgarn Craton clastic–volcanic sequences, and the presence of gold mineralization and banded iron-formation (BIF). A Lower Proterozoic age, however, was not discounted, with the sedimentary rocks (e.g. BIF) tentatively being correlated with the Mount Bruce Supergroup in the Ashburton region. MacLeod (1970) considered the structure of the Peak Hill area as a major synclinorium, with the granite of the Goodin and Marymia Inliers enclosing the Archaean sedimentary sequence (Peak Hill Schist and part of the Yerrida Group). The mafic rocks of the Narracoota Formation (Bryah Group; Pirajno

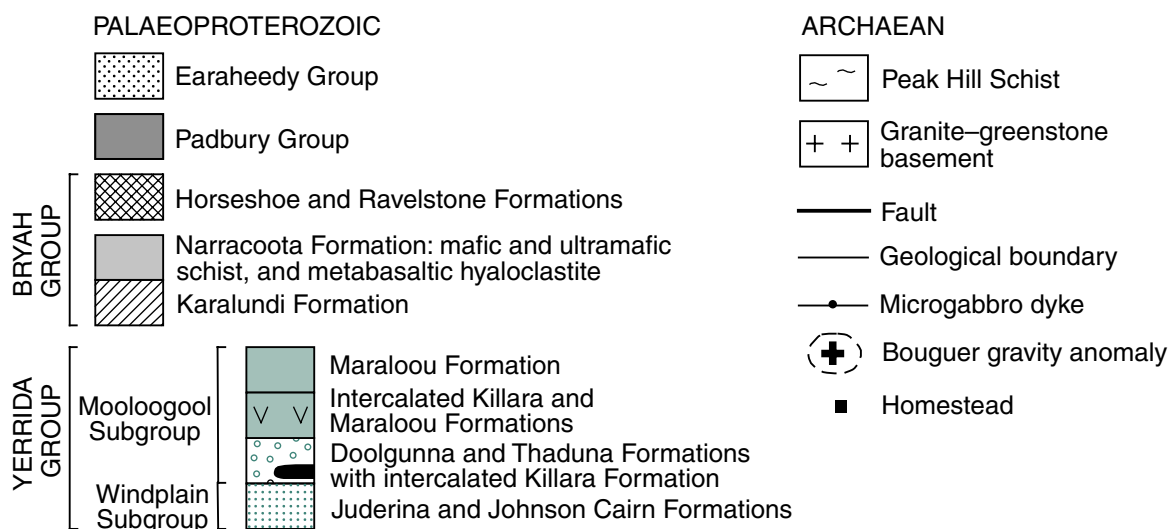
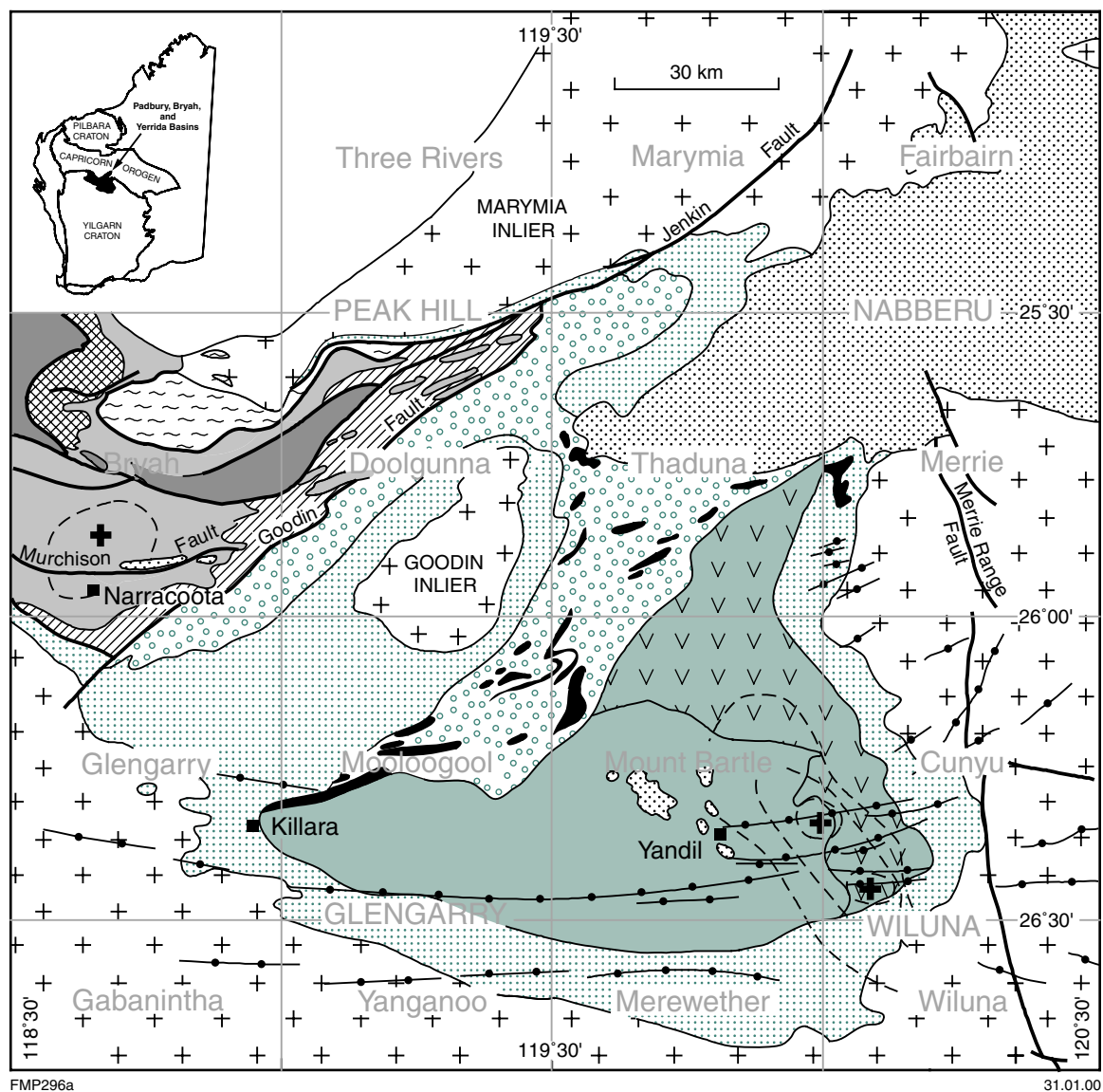


Figure 1. Simplified geological map of the Bryah, Padbury, and Yerrida Basins (after Pirajno et al., 1998c)



Gee (1987)		Gee and Grey (1993)		Occhipinti et al. (1997); Pirajno et al. (1998c; this study)				
PADBURY BASIN/GROUP	Millidie Creek Formation  Robinson Range Formation  Wilthorpe Formation					TECTONIC CONTACT	*PADBURY BASIN/GROUP	Millidie Creek Formation Robinson Range Formation Wilthorpe Formation  Labouchere Formation
	Unconformity							
GLENGARRY BASIN/GROUP	Labouchere Formation Horseshoe Formation Thaduna Greywacke Narracoota Volcanics Karatundi Formation Doolgunna Formation Johnson Cairn Shale Juderina Formation Crispin Conglomerate Maraloou Formation Finlayson Sandstone						GLENGARRY BASIN/GROUP	Maraloou Formation Narracoota Volcanics Thaduna Greywacke  Doolgunna Formation Johnson Cairn Shale Juderina Formation (Finlayson Sandstone Member)
	Peak Hill Metamorphics	ARCHAEAN BASEMENT	*Windplain Subgroup	Johnson Cairn Formation Juderina Formation (Finlayson and Bubble Well Members)				
				*BRYAH BASIN/GROUP	Horseshoe Formation *Ravelstone Formation *Narracoota Formation Karatundi Formation			
							Peak Hill Schist	

NOTE: \*New or redefined units (Occhipinti et al., 1997)

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**Figure 2. New stratigraphy of the Yerrida Group, compared with previous stratigraphy of the Glengarry Group**

et al., 2000) were similarly assigned an Archaean age and thought to intrude the sedimentary units. The sedimentary rocks around Thaduna mine and to the south were assigned to the Bangemall Group. Later, Horwitz (1975) assigned a Lower Proterozoic age to the whole of the Glengarry Group and correlated these rocks with similar lithologies in the Earraheedy Basin and, farther north, with the Wyloo and Manganese Groups.

The work of Hall and Goode (1975, 1978) was instrumental in defining the Nabberu Basin. This basin contained the Earraheedy, Glengarry, and Padbury Sub-basins. Their geological map (Hall and Goode, 1978, fig. 2) presented the currently accepted tectonic and lithological framework, that is, the unconformable relationships between the Archaean granitoids and later sedimentary units, and between the sedimentary units of the Glengarry and Bangemall Groups. Most of the sedimentary units of the Glengarry and Earraheedy Groups, with the exception of the Peak Hill Beds (later named the Peak Hill Metamorphics by Gee, 1979), are named in this work.

Bunting et al. (1977) suggested that there was an unconformity between a younger Earraheedy Group to the east and an older Glengarry Group to the west, and that the Glengarry and Earraheedy Sub-basins should be elevated to basin status. Horwitz and Smith (1978) considered, on the basis of the presence of a common dyke swarm and the distribution of stresses in the Yilgarn and Pilbara Cratons, that prior to the earliest sedimentation, both Archaean blocks were part of a single craton. The authors also attributed a deep-water origin to the turbidite sequences of that part of the Glengarry Basin, now referred to as the Yerrida Basin, and described the presence of olistostromes in this unit. They correlated some of these olistostromes with the Frere Formation of the Earraheedy Group, thus considering this group to be older than the Glengarry Group.

The GSWA began systematic 1:250 000-scale mapping in 1975. The results were published in a series of papers and Explanatory Notes by Bunting et al. (1977), Gee (1979, 1987; PEAK HILL), Elias et al. (1982; GLENGARRY), Elias and Williams (1980; ROBINSON RANGE), and Elias and

Bunting (1982; WILUNA). Gee (1990) presented a synthesis of the whole of the Nabberu Basin (which includes the Bryah, Padbury, Yerrida, and Earaaheedy Basins), whereas Bunting (1986) integrated all investigations for the Earaaheedy Basin.

The stratigraphy of the Glengarry Group was revised and formalized by Gee (1979, 1987). Gee and Grey (1993) eventually elevated the Glengarry Sub-basin to basin status (see above). The new basin was defined to include the Padbury Sub-basin and the superseded Glengarry Sub-basin. The Earaaheedy Sub-basin was also elevated to basin status. Gee and Grey (1993) also described the stratigraphy and structure of the Glengarry Basin, with emphasis on evaporites and stromatolites of the Juderina Formation.

Windh (1992) worked on the tectonics and metallogenesis of the Glengarry Basin. This work envisaged the presence of syndepositional faults during the formation of the Glengarry Basin as an intracratonic rift at about 1.9 Ga. The intersection of the northward extension of the Murchison greenstone belt and the northward extensions of the Wiluna greenstone belt was considered to be a locus of voluminous magmatism. Basin closure involved north-south crustal shortening ( $D_1$ ), tight folding, reverse faulting, and development of penetrative cleavage.

Grey (1994a) described new stromatolite taxa from the Glengarry Group. These are considered diagnostic of this group and allow the Glengarry Group to be differentiated from lithologically similar units of the Earaaheedy Group.

In the early stages of the present study, Pirajno et al. (1996) subdivided the Glengarry Basin into three distinct basins: the Padbury Basin in the west, Bryah Basin in the centre, and Yerrida Basin in the east (Fig. 1).

Interim conclusions from the recent remapping of the Yerrida Basin were presented by Pirajno and Occhipinti (1995), Pirajno and Davy (1996), Pirajno (1996), Pirajno et al. (1996), Occhipinti et al. (1997), Pirajno and Preston (1998), Pirajno et al. (1998c) and Tyler et al. (1998); and in maps and Explanatory Notes by Adamides (1998), Bagas (1998), Dawes and Pirajno (1998), Pirajno and Adamides (1998), Pirajno and Occhipinti (1998), Pirajno et al. (1998a,b,c), and Adamides et al. (1999). Krapez and Martin (1999) investigated the rift basins of the Nabberu Province using concepts of sequence stratigraphy. However, we disagree with the recently published model of Krapez and Martin (1999) for the Yerrida Basin, which is based on correlations and stratigraphic relationships that have already been shown to be invalid (Occhipinti et al., 1997; Pirajno et al., 1995, 1996, 1998c).

## Regional tectonic setting

The Yerrida Basin is situated along the northeastern margin of the Archaean Yilgarn Craton, and separates the Bryah and Padbury Basins in the west from the Earaaheedy Basin to the east. Together these basins extend for approximately 650 km in east-west to east-southeasterly directions, forming the southern part of the Capricorn Orogen (Fig. 1).

The Capricorn Orogen is situated between the Pilbara and Yilgarn Cratons, and can be traced for more than 1000 km with northwesterly to westerly trends, forming a broad belt of deformed, low-grade volcano-sedimentary belts, low- to high-grade metamorphic belts, and granitoid intrusions (Fig. 1). The Capricorn Orogeny occurred at c. 1.8 Ga and was the result of the collision between the Pilbara and the Yilgarn Cratons (Occhipinti et al., 1999; Tyler, 1999). It involved the closure of an intervening ocean, formation of a back-arc basin, and possibly the accretion of microcontinental fragments (Tyler and Thorne, 1990; Myers, 1993; Myers et al., 1996; Tyler et al., 1998; Occhipinti et al., 1999). Other tectonic units, such as the Archaean Narryer Terrane, Marymia Inlier, Sylvania Inlier, and parts of the Hamersley Basin, were also affected by the Yilgarn-Pilbara collision (Tyler and Thorne, 1990; Myers et al., 1996; Tyler et al., 1998). The Yerrida Basin may have formed, at approximately 2.2 Ga, as a pull-apart structure related to the development of easterly trending strike-slip movements and regional sinistral faults. Alternatively, the basin may have been formed as a passive rifted continental margin. These issues are examined more fully in **Basin development and tectonic evolution**. The convergence between the Pilbara and Yilgarn Cratons between 1.84 and 1.78 Ga (Tyler, 1999) resulted in the deformation of the western and northern margins of the Yerrida Basin.

The Palaeoproterozoic sedimentary and volcano-sedimentary successions are unconformable on the northern margin of the Yilgarn Craton, whereas to the north and northwest they are either unconformably overlain by or faulted against rocks of the Bangemall and Officer Basins and Archaean granitic inliers. These granitic inliers comprise the Marymia Inlier in contact with the Bryah, Yerrida, and Earaaheedy Basins; the Goodin Inlier enclosed within the Yerrida Basin; and the Malmac Inlier, about 300 km to the east on the northern side of the Earaaheedy Basin. The Goodin and Marymia Inliers partly controlled the sedimentation of the Doolgunna and Thaduna Formations of the Yerrida Group.

## Goodin Inlier

The Goodin Inlier (*AgGI*) is a fragment of Archaean granitic basement, approximately  $30 \times 45$  km, in the western part of the Yerrida Basin (Plate 1). The rocks of the inlier are unconformably overlain by the basal units of the Yerrida Group. The basal unconformity is well exposed in the northwestern and southeastern parts of the inlier (Plate 1), where the granite is overlain by quartz arenite of the Juderina Formation (Finlayson Member). However, contacts in the southwest are complicated by tectonic slices of quartz arenite within the granite. The inlier played a significant role in the evolution of the Yerrida Basin.

It is not clear whether the Goodin Inlier is structurally part of the Murchison Province, Southern Cross Province or Eastern Goldfields Province of the Yilgarn Craton. East-southeasterly trending dykes that intruded the inlier may either be part of the east-northeasterly trending dyke swarm in the Murchison Province (Myers and Hocking,

1998), or of the easterly trending swarms of the northern Yilgarn Craton, some of which cut through rocks of the Yerrida Group (Plate 1). In the former case, the inlier would have undergone substantial rotation after the emplacement of the dykes; in the latter case, only a small amount of rotation is implied. Mafic dykes are discussed further in **Mafic dykes**.

Granitic outcrops of the Goodin Inlier are commonly weathered, with low breakaways and kaolinitized material on the walls, and fresher rock on the floors. The best granitoid outcrops are around Utahlarba Spring and Granite Bore. One sample collected from the Granite Bore area was dated using the sensitive high-resolution ion microprobe (SHRIMP), yielding a zircon crystallization age of  $2624 \pm 8$  Ma (Nelson, 1997; Plate 1).

The inlier dominantly consists of medium-grained monzogranite, with average grain size of around 4–5 mm. Porphyritic varieties, with feldspar exceeding 8 mm in size, are locally present, as are micropegmatitic and aplitic phases. The monzogranite contains K-feldspar (12 to 29 vol.%), plagioclase (12 to 26 vol.%), quartz (26 to 46 vol.%), and biotite (up to 9 vol.%) as main minerals. Accessory phases include epidote, muscovite, sericite, rutile, apatite, and zircon. In places, fluorite and allanite may be present. Fluorite is a late-forming euhedral phase along grain boundaries or infilling microfractures; allanite is euhedral and typically zoned. Quartz is present in subhedral aggregates interstitial to the plagioclase, or forms recrystallized polygonal mosaics replacing the feldspars. In the QAPF classification of Streickeisen (1976), these samples plot in the field of monzogranite to syenogranite.

With the exception of the tectonic contact at the southwestern margin of the Goodin Inlier and local development of foliation, the monzogranite is undeformed. Deformed varieties are characterized by the development of a foliated sericitic matrix enclosing lenticular feldspar and polycrystalline quartz, and complete destruction of plagioclase and partial preservation of K-feldspar.

Near the mafic dykes, contact metamorphism of the monzogranite is characterized by strongly sericitized feldspar, locally resulting in the complete replacement of the mineral by fine-grained sericite. The feldspars are commonly surrounded by micrographic reaction rims.

With the exception of a small outcrop of amphibolite in the northeastern parts of the inlier, no greenstone rocks are present. The amphibolite has a doleritic texture and contains quartz, epidote, chlorite, and clinozoisite replacing plagioclase, associated with skeletal crystals of ilmenite altered to titanite, and actinolite after clinopyroxene. Micrographic intergrowths of quartz and plagioclase are interstitial to the other silicates, with the plagioclase altered to a mixture of euhedral clinozoisite and quartz.

The Goodin Inlier influenced sedimentation patterns in the Yerrida Basin. As explained more fully below, the inlier is surrounded by clastic sedimentary rocks (Doolgunna and Thaduna Formations), whose provenance indicate both granitic and sedimentary sources. The

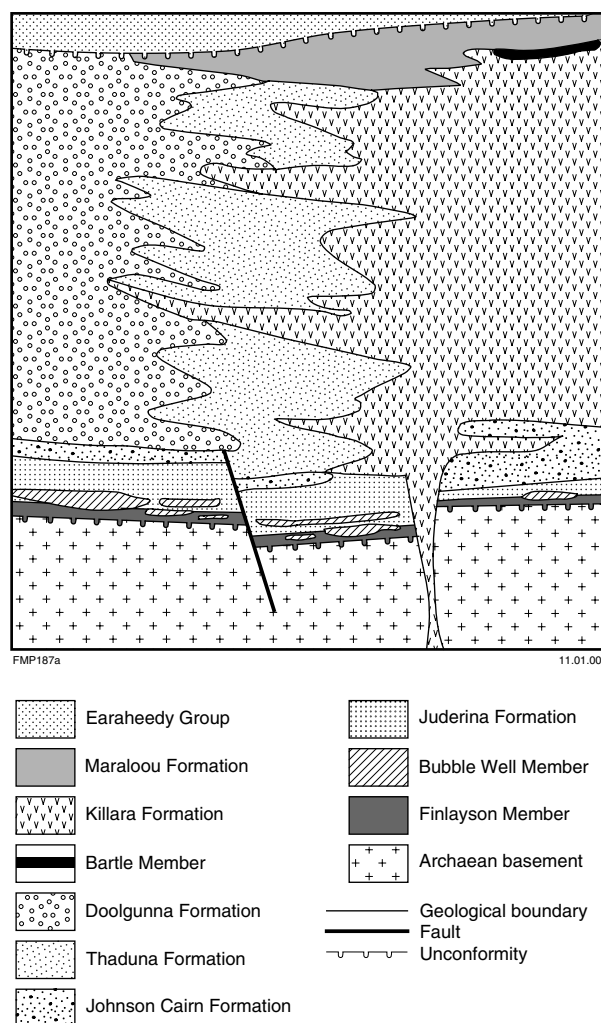
sedimentary component includes stromatolitic cherts and evaporites, most probably sourced from the Juderina Formation. This suggests that the inlier was uplifted after the deposition of the Juderina Formation and stripped of its sedimentary cover (Fig. 1).

## Palaeoproterozoic Yerrida Group

The Yerrida Group outcrops in the eastern and south-eastern parts of the former Glengarry Basin of Gee and Grey (1993), and includes siliciclastic rocks, carbonate sedimentary rocks, and mafic volcanic and hypabyssal rocks. The group unconformably overlies, or is in tectonic contact with, Archaean granite–greenstone rocks of the Yilgarn Craton and the Marymia and Goodin Inliers (Fig. 1, Plate 1). Its northwestern boundary with the Bryah Group is marked by the Goodin Fault. In the eastern Yerrida Basin, the Yerrida Group is unconformably overlain by the Palaeoproterozoic Earahedy Group (Fig. 1, Plate 1).

The age of the Yerrida Group is constrained between c. 2.2 and c. 1.9 Ga. A Pb–Pb isochron of  $2173 \pm 64$  Ma was obtained from stromatolitic carbonate rocks of the Bubble Well Member (Windplain Subgroup in the lower part of the Yerrida Group; Fig. 2, Plate 1; Woodhead and Hergt, 1997), which gives a depositional age for the stromatolitic carbonate rocks. In addition, Russell (1992) recorded anomalously high  $d^{13}\text{C}_{\text{carb}}$  of between +9 and +9.36 per mL for a carbonate from near the base of the Bubble Well Member. These values are consistent with a major positive  $d^{13}\text{C}_{\text{carb}}$  shift at  $2200 \pm 100$  Ma in the Fennoscandian Shield and elsewhere (Melezhik et al., 1997). Pb–Pb dating of stromatolitic carbonate rocks from the Yelma Formation gave ages of  $2008 \pm 68$  Ma and  $1946 \pm 71$  Ma (Russell et al., 1994), whereas studies of stromatolite taxa from the unconformably overlying carbonate rocks of the Yelma Formation (Earahedy Group) suggest ages of between 1.9 and 1.8 Ga (Grey, 1994a).

The Yerrida Group is divided into the Windplain and Mooloogool Subgroups, each the product of different tectonic settings (Pirajno et al., 1995). Lithostratigraphic relationships between units of these two subgroups are schematically shown in Figure 3. The Windplain Subgroup contains the Juderina and Johnson Cairn Formations. The sedimentological characteristics are indicative of a sag basin or pre-rift depression (Pirajno et al., 1995, 1996). The Juderina Formation consists of siliciclastic, carbonate, and evaporite rocks and contains the Finlayson and Bubble Well Members. Importantly, no basal conglomerates are present. The Finlayson Member consists of a thin (<100 m) and widespread basal quartz arenite unit, which commonly displays herringbone and trough cross-bedding and multidirectional ripple marks. The Finlayson Member is overlain by or intercalated (or both) with chertified stromatolitic carbonate and evaporitic sedimentary units of the Bubble Well Member. The Juderina Formation is unconformable on or faulted against the Archaean basement rocks of the Goodin



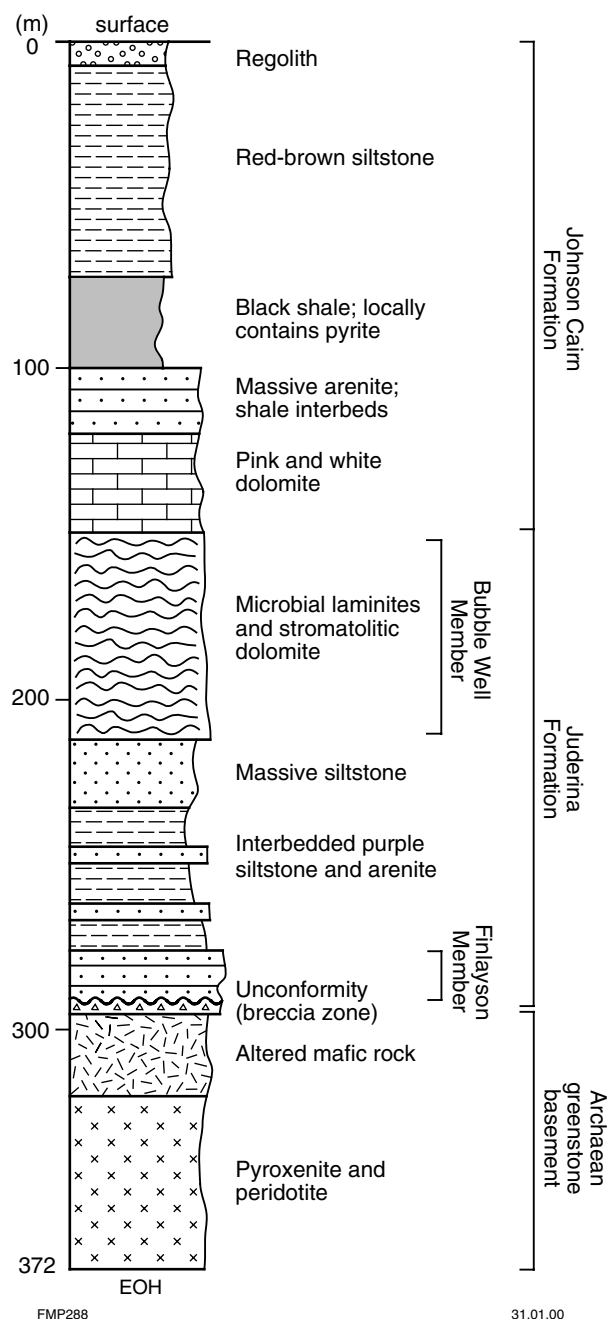
**Figure 3. Schematic relationships of stratigraphic units of the Yerrida Group (vertical length reflects relative thicknesses)**

and Marymia Inliers, and the Yilgarn Craton. This formation is conformably overlain by the Johnson Cairn Formation, which is dominantly composed of argillaceous rocks.

Field and sedimentological evidence indicate that the siliciclastic and evaporitic rocks of the Windplain Subgroup were deposited in supratidal and intertidal environments. It is also important to note that no conglomerates are present in the basal units and that the mature quartz arenites of the Juderina Formation rest unconformably on Archaean basement. This suggests that the Juderina sediments were sourced from a peneplained area. The unconformity between the basal Windplain Subgroup and the Archaean basement is essentially undisturbed along the southern and eastern margins of the Yerrida Basin, but highly tectonized along the northern and western contacts with the Marymia Inlier and the Bryah Group. A stratigraphic column of the Windplain Subgroup, derived from drillcore in the western part of the Yerrida Basin, is shown in Figure 4.

The Mooloogool Subgroup conformably overlies the Windplain Subgroup and was deposited in a rift-basin

setting (Pirajno et al., 1995, 1996). The Mooloogool Subgroup is divided into the Thaduna, Doolgunna, Killara, and Maraloou Formations. The sedimentary rocks of the Thaduna and Doolgunna Formations (conglomerates and turbidite-facies rocks) were deposited in a high-energy setting and, as such, these rocks herald an abrupt change from the shallow, lower energy setting of the Windplain Subgroup. The distribution of these two formations is centered around the Goodin Inlier, in a broad northeasterly trending belt (Fig. 1; Plate 1). The Thaduna and Doolgunna Formations were largely sourced from the



**Figure 4. Summary log of drillhole QMW 83-1 and details of the stratigraphy of the Juderina Formation (after Pirajno and Adamides, 1998; width of column reflects relative resistance to weathering)**

Goodin and Marymia Inliers and they interdigitate, testifying to complex lateral-facies changes. The Doolgunna Formation is a succession of conglomerates, turbidite-facies rocks, and diamictite units, the latter being the result of mass-wasting sourced from rocks overlying and including the Goodin Inlier. These sediments accumulated in a northeasterly trending graben-like structure (Doolgunna graben; Pirajno, 1996; Pirajno and Occhipinti, 1998) on the eastern side of the Goodin Fault (Fig. 1). The Thaduna Formation is typically a turbiditic succession dominated by coarse- to fine-grained wackes, containing lithic fragments of volcanic rocks, shale, and siltstone. Petrographic studies show that some of these volcanic rocks were sourced from Archaean greenstones within the Marymia Inlier, and others from the Killara and Narracoota Formations. The Doolgunna and Thaduna Formations also interdigitate with the tholeiitic volcanic and intrusive rocks of the Killara Formation, indicating that volcanism and clastic sedimentation were concurrent in rift-related depocentres (Mooloogool rift; Pirajno, 1996). In the east and southeast, tholeiitic rocks of the Killara Formation overlie and intrude the Windplain Subgroup, and are overlain by the Maraloou Formation. In the east, mafic sills of the Killara Formation intrude rocks of the Juderina Formation.

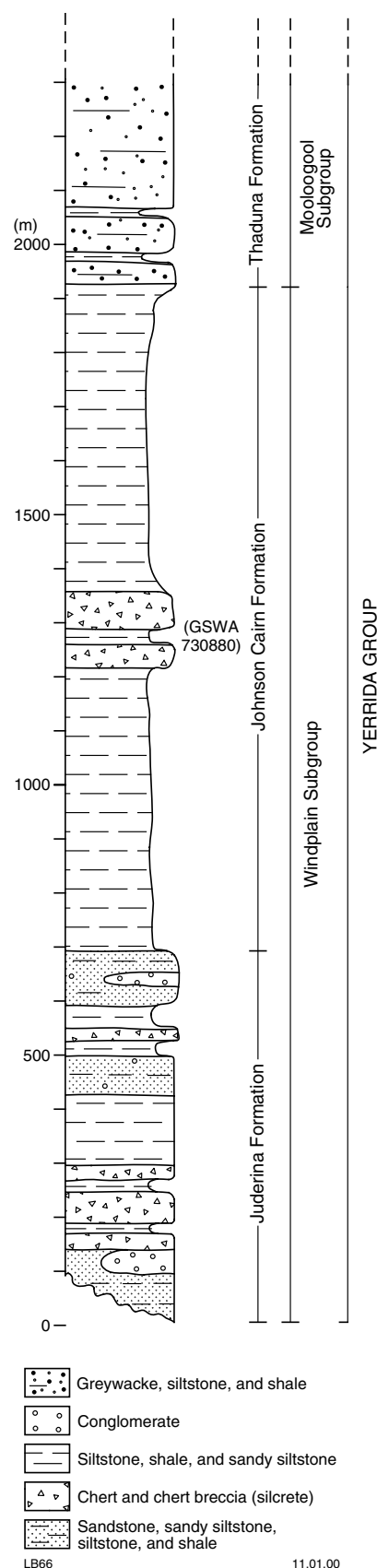
The Maraloou Formation includes carbonaceous argillite, marl, dolostone, and minor chert, and its deposition represents a marked deepening of the basin. In the west, the contact between the Maraloou and Killara Formations is transitional over a stratigraphic thickness of approximately 150 m, with the volcanic Killara component consistently decreasing with stratigraphic height. Peperite margins in the mafic lavas and sills of the Killara Formation indicate that the mafic magmas were emplaced into or onto (or both) unconsolidated wet sediments of the Maraloou Formation. In the east, however, the Maraloou Formation is unconformable on the Killara Formation and conformable over the Thaduna and Doolgunna Formations. This may reflect onlap due to contemporaneous block faulting in the eastern areas.

## Windplain Subgroup

### Juderina Formation

The Juderina Formation (Occhipinti et al., 1997) is a predominantly shallow water sequence of quartz sandstone, with lesser amounts of siltstone, chert breccia, and conglomerate, at the base of the Yerrida Group (Figs 2 and 3). The formation is exposed around the margins of the Yerrida Basin, but is inferred to be present throughout, forming the floor of the basin. The thickness of the Juderina Formation varies considerably throughout the Yerrida Basin. At the type locality, 3.5 km north of Juderina Bore on DOOLGUNNA, it is only 30 m thick (Gee, 1979), but in reference sections on MARYMIA and MOOLOOGOL, it is between 300 and 2000 m thick (Figs 4 and 5).

The Juderina Formation is in faulted or unconformable contact with Archaean basement rocks, and conformably overlain by the Johnson Cairn Formation, with the contact



**Figure 5. Stratigraphy of the Windplain Subgroup on MARYMIA (after Bagas, 1998; width of column reflects relative resistance to weathering)**

defined by the top of the last quartz arenite unit. The unconformity at the base of the Juderina Formation has not been observed in the eastern parts of the Yerrida Basin. However, Elias and Bunting (1982) described the unconformity 2 km west of Lanagan Bore on WILUNA. They reported an 8 m-thick lens of conglomerate and pebbly arenite, passing laterally and vertically into coarse-grained quartz arenite. Pebbles in the conglomerate consist mainly of vein quartz, with minor banded chert, presumably derived from the Archaean basement.

Elsewhere on WILUNA, the unconformity is marked by a band of thinly bedded granule conglomerate. Clasts consist of quartz and jasper set in a matrix of poorly sorted and weakly kaolinitic quartz sandstone. The basal arenite units are flaggy bedded and ripple marked. A generalized section through the Juderina Formation in the area 5 to 10 km west and southwest of Mount Alice is shown in Figure 6.

The basal units of the Juderina Formation are commonly mature quartz arenite and subordinate quartz siltstone. These show sedimentary structures (ripple marks, herringbone cross-laminations) indicative of shallow-water sedimentation. Units that exhibit these sedimentological characteristics are referred to as the

Finlayson Member. The Bubble Well Member is a distinctive unit of stromatolitic chert and chert breccia in the middle of the formation. Both are discussed more fully below. In the eastern parts of the Yerrida Basin, the formation has been considerably thickened by the intrusion of dolerite sills.

Higher in the sequence, the Juderina Formation becomes increasingly thicker bedded, and dominated by grey quartz arenite, commonly with a purple hematitic surface colouration. Sand grains in the upper quartz arenite are commonly more angular, and cross-bedding and ripple marks are not as well developed as in the basal units. The arenite is composed of packed aggregates of 0.3 – 0.4 mm, rounded to subrounded quartz grains with subordinate interstitial kaolinite, and traces of rutile, zircon, and tourmaline. Approximately 2.5 km northwest of Goosie Bore, the arenite contains nodules up to 10 cm in diameter, or tabular bodies (up to 30 cm long) with well-developed cubic voids, probably after halite.

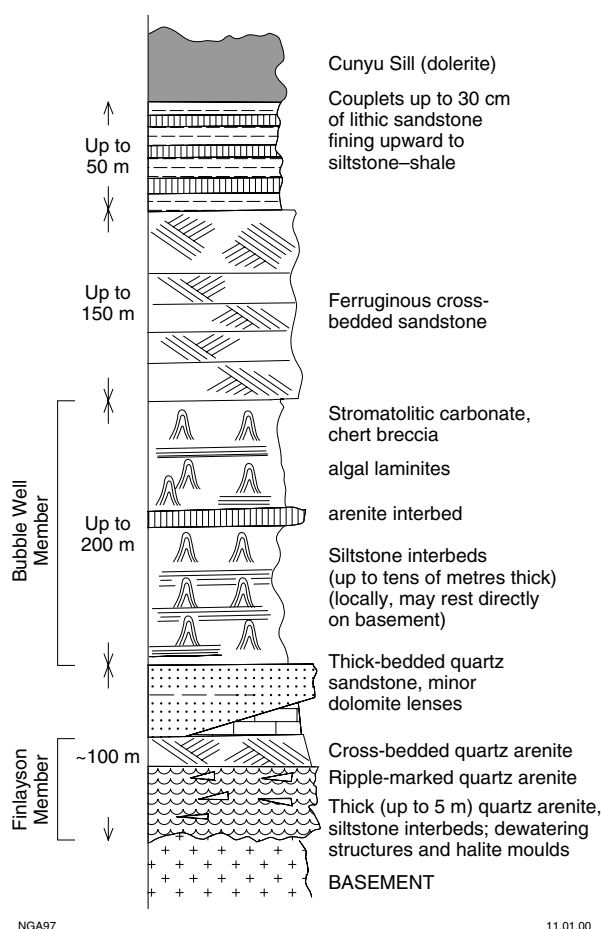
Quartz arenite of the Juderina Formation is typically fine to medium grained and moderately sorted. Ferruginous variants contain white mica within the clay matrix and are associated with platelets of hematite. Siltstone laminae are a few millimetres thick and comprise angular quartz averaging 0.1 mm in diameter enclosed in a hematitic matrix. The argillaceous laminae contain fine disseminations of iron hydroxides.

Thick-bedded quartz arenites, southeast of the Glengarry Range, form hills and ridges between swales of siltstones and shales. Quartz arenite is medium grained, with angular grains, intraclast moulds, and abundant mud clasts. It is silica cemented and poorly sorted, and forms beds commonly more than 1 m thick. Thicker beds have massive bases, with laminations near the top, whereas thinner arenite units interbedded with the siltstones are parallel laminated. The quartz arenite contains local kaolinitized feldspars and sparse lithic clasts. Laminated siltstone contains sparse feldspar and weathered muscovite with minor detrital tourmaline in a matrix of quartz and kaolinitic clays.

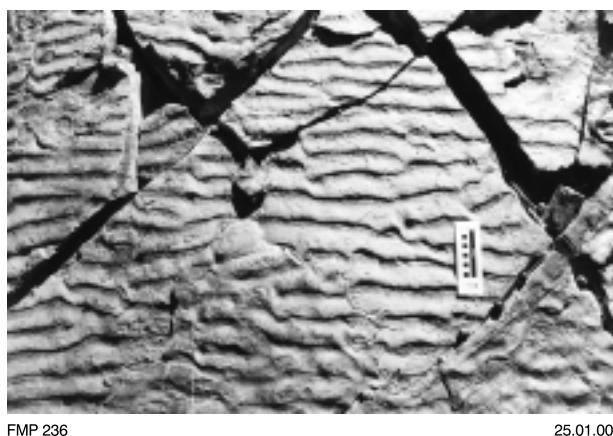
Shale and quartz siltstone form up to 30% of the Juderina Formation, but are commonly recessive. The siltstone varies from white to light grey and is typically finely laminated. Siltstone consists of quartz grains (around 0.05 mm in diameter) in a matrix of very poorly crystalline illite and kaolinite-group clays. The quartz shows irregular crystal boundaries and is partly diffused into the clay matrix. Local white mica is altered along grain margins to clays. Fine-grained cherty types are characterized by very finely crystalline interstitial clays, which display preferred orientation parallel to lamination, probably as a result of diagenetic compaction.

### Finlayson Member

The Finlayson Member is at the base of the Juderina Formation, close to the unconformity with the Archaean basement. The Finlayson Member is typically a cream-coloured, silica-cemented quartz arenite forming individual beds a few centimetres to 1 m thick. Both



**Figure 6. Stratigraphy of the Juderina Formation, near Mount Alice (width of column reflects relative resistance to weathering)**



**Figure 7. Quartz arenite with ripple marks from the Finlayson Member of the Juderina Formation. Scale bar has 1 cm graduation**

symmetrical and asymmetrical ripple marks are present. Ripple crests are straight, although sinusoidal forms are also present. Wavelengths vary widely from a few centimetres to tens of centimetres. Small-scale ripples with flat tops (Fig. 7) suggest very shallow water to emergent conditions. Nodular chert concretions and halite moulds are locally developed.

Quartz arenites of the Finlayson Member are characterized by very well sorted and well-rounded quartz grains, 0.2 – 0.5 mm in diameter. Heavy mineral concentrates from this unit contain subhedral zircon and tourmaline, associated with rounded brown biotite and rutile. Well-rounded zircon and tourmaline are subordinate, suggesting that the basal quartz arenite is mainly derived directly from erosion of granitic source areas, with little second-generation reworking.

Good exposures of the Finlayson Member are present in the southern and southwestern part of the Yerrida Basin (Plate 1). Here, they are part of a broad, approximately easterly trending, arcuate band of shelf-facies rocks that lies unconformably on granite–greenstone rocks (Plate 1). On MOOLOOGUOL the quartz arenite dips between 5° and 20° to the north, and contains well-preserved ripple marks and laminae of clay platelets. A limited number of measurements (<20) taken on asymmetrical ripples suggest palaeocurrent directions from the northeast and southwest. Mappable bands of hematite-rich arenite less than 10 m thick are locally intercalated with the quartz arenite. They consist of round quartz grains, with authigenic overgrowths of silica and fine dustings or coatings of hematite around the quartz grains. Detrital tourmaline crystals (probably schorl) are also present. They are interpreted as a continental red bed sequence. Red beds became significant from about 2000 Ma and formed in hot climates under continental oxidizing conditions, commonly at latitudes of 30° or less (Keary and Vines, 1996). Continental red beds are commonly associated with evaporites, as is the case for rocks of the Finlayson Member, which are intercalated with evaporites of the Bubble Well Member.

### Bubble Well Member

The Bubble Well Member was defined by Occhipinti et al. (1997) as a unit of chertified carbonate and evaporitic sedimentary rocks, estimated to be approximately 160 m thick, within the Juderina Formation. The member is best developed in the southeastern Yerrida Basin. The type section is at Eagle Roost on WILUNA (Gee and Grey, 1993); here, Gee and Grey (1993) carried out detailed studies of evaporitic and stromatolitic features of this unit, and proposed a sabkha-type depositional environment. The member is a distinct facies of the Juderina Formation that does not occupy a unique stratigraphic position. Around Goosie Bore (CUNYU), the member lies on granite basement, but it is more commonly found overlying either the Finlayson Member or quartz sandstone units. Stratigraphic relationships with other units of the Windplain Subgroup are shown in Figure 3. Field and petrographic evidence suggest that the dominant precursor lithology was stromatolitic carbonate, with evaporitic sediment intercalations and early diagenetic displacement.

The Bubble Well Member typically consists of layers of chert breccia and chert with wavy laminations, derived from dolomitic microbial laminites, and chert-replaced stromatolitic dolomite intercalated with evaporitic layers. The member is commonly a rusty-weathering, cream-coloured chert and chert breccia with diffuse grey banding. Rounded nodules, probably diagenetic, are widespread, and delicate, wavy microbial laminations are present in a few facies. Species of the stromatolite *Wilunella glengarrica* and *Segosia finlaysonensis* were identified in outcrops 2 km north of Top Kukabubba Well (Grey, 1994a,b). The former is present as domes up to 2 m in diameter; the latter is a columnar form. Along strike from this outcrop, dolarenite units are interbedded with cross-laminated quartz arenite. The dolarenite units, which are too small to show on the geological map, consist of peloidal or locally oolitic forms. The peloids average 0.4 mm in diameter, are commonly elliptical, and set in a weakly iron stained cherty matrix. Quartz grains are intermixed with the peloids and locally form the cores of oolites. Breccia bands are locally interbedded with subordinate, weakly ferruginous, well-sorted sandstone. Ripple-marked quartz arenite 4.9 km northwest of Top Kukabubba Well is overlain by a thick sequence of chert and chert breccia, locally with elongate evaporitic pseudomorphs and stromatolitic laminations. Cherty bands up to 2 cm thick are present in some facies, alternating with finely laminated chert of probable microbial origin. These features together suggest a shallow-water, probably intertidal, environment with interfingering relationships between carbonate lagoon and bank deposits (now represented by chert breccia) and quartz sandstone in washovers and channels, and local development of evaporitic minerals and stromatolites in barred lagoons.

Chertified evaporitic units, locally alternating with argillite beds, contain cubic, bladed, needle, rosette, and swallow-tail crystal pseudomorphs, a few up to 3 cm long, which are interpreted to have been evaporite minerals such as halite, gypsum, and anhydrite. In places nodular forms are present; these are probably replacing anhydrite nodules. A small outcrop of stratified chert, about 4 km south of North Bore is characterized by

microbial-like laminae and fragmented laminated textures with spherulitic or stellate pseudomorphs. The rock contains microcrystalline and cryptocrystalline quartz, minor sericite, euhedral barite crystals, albite, apatite, and isolated K-feldspar crystals. Spherulitic pseudomorphs are up to 10 mm in diameter and consist of radiating aggregates of microcrystalline and polycrystalline quartz, interpreted to be pseudomorphs after anhydrite. Unidentified radiating acicular or blade-like crystals could be pseudomorphed gypsum. El Tabakh et al. (1999) interpreted the Bubble Well Member evaporites as having formed displacively within fine muds, during intermittent flooding and dry periods of a saline environment. Precipitation of evaporite minerals from interstitial brines occurred in the early diagenetic stages, before cementation of the sediments.

On CUNYU the Bubble Well Member is present as lenticular outcrops, commonly between basal arenite of the Finlayson Member and overlying thick bedded arenites. At the southern boundary of CUNYU, chert and chert breccia of the Bubble Well Member is both well bedded, with subrounded bioherms, and a chaotic breccia facies, with intervening thin semicontinuous chert bands. Stromatolitic bioherms are widespread in the cherts and diagenetic chert nodules are abundant. The cherts are in turn underlain by cream-coloured and ripple-marked quartz arenite close to the basal contact.

In the western Yerrida Basin (Plate 1) on GLENGARRY and at a locality approximately 5 km south of Karalundi Homestead, the Bubble Well Member consists of siltstone, laminated chert, and a crudely bedded chert breccia. The chert rocks contain bioherms of a new stromatolite form, *Kussoidella* (Gee and Grey, 1993). Parallel laminations, soft-sediment deformation structures, cross-bedding, and planar bedding surfaces in the original sediment are commonly preserved. The chertified sedimentary rock is characterized by cryptocrystalline and microcrystalline quartz, chalcedonic quartz, and minor iron oxides. The upper and lower contacts of the Bubble Well Member have not been directly observed, but about 3 km north of Referendum Bore, the Bubble Well Member clearly lies above the Finlayson Member.

### **Southwest contact of the Goodin Inlier with the Juderina Formation**

A series of shear zones trend west-northwest, with moderate dips (45° to 50°) to the north or south, on the southwestern margin of the Goodin Inlier, around Utahlarba Spring. Quartz veins are present, oriented oblique to the shearing. Thin outliers of laminated and locally ripple marked quartz arenite are associated with these shear zones. The contact with the underlying granite is unconformable, starting with a basal unit of parallel-laminated arenite followed by cream-coloured, locally cross-bedded arenite. The rock is cut by steeply dipping to vertical longitudinal joints. This jointing becomes progressively more closely spaced in a southerly direction across the outlier and is associated with silicification and quartz veining, suggesting the presence of a faulted contact.

Vesicular mafic rocks (possibly volcanic) are present in a number of outcrops, extending northwest from about 2 km east of Brownly Bore. The presence of these rocks signifies magmatic activity contemporaneous with the earliest sedimentation of the Yerrida Basin in this area. This volcanism may be correlated with the Killara Formation (see below), which includes similar mafic rocks exposed at higher levels in the Yerrida Group succession. The presence of these mafic volcanic rocks in the lower units of the Yerrida Group stratigraphy, coupled with their absence from the same basal units elsewhere, suggests tectonic activity and early development of magma-tapping fractures along the southern margin of the Goodin Inlier.

## **Johnson Cairn Formation**

The Johnson Cairn Formation, originally the 'Johnson Cairn Shale' of Gee (1987) and redefined by Occhipinti et al. (1997), is a succession of varicoloured iron-rich shale, with graded silty layers and thin dolomite bands. The formation overlies the Juderina Formation in the areas northeast of the Thaduna copper mine and around the Goodin Inlier. The boundary with the underlying unit is taken as the topmost bed of quartz arenite. At the type area, 13 km northeast of the Thaduna copper mine on the Johnson Cairn hill, the formation rests conformably on the Juderina Formation and consists of laminated, varicoloured iron-rich shale interbedded with minor carbonate (Gee, 1987). The formation is up to 1250 m thick and conformably overlain by the Thaduna Formation of the Mooloogool Subgroup (Bagas, 1998).

On MOUNT BARTLE the Johnson Cairn Formation is a sequence of laminated purple- to cream-coloured siltstones and is considerably thinner, probably not exceeding 100 m (Dawes and Pirajno, 1998). On MOOLOOGOL the most extensive outcrops form a broad east-northeasterly trending belt in the central part of the map sheet, where it is interbedded with mafic rocks of the Killara Formation. Outcrops of the Johnson Cairn Formation are also present in the area around Mooloogool Homestead. Here, the Johnson Cairn Formation includes thinly bedded (up to 0.3 m thick) argillaceous siltstones with local thin dolomite beds and minor lithic and quartzose wacke. The siltstone consists of variable mixtures of kaolinite and illite, commonly associated with iron hydroxides. Four kilometres west of Mooloogool Homestead, a moderately sorted quartz wacke has rounded quartz grains in a kaolinitic matrix, and is locally interbedded with hematitic shale. The quartz wacke consists of subangular to subrounded polycrystalline quartz in a matrix of illite and kaolinite. The matrix also contains weathered white mica and rarer tourmaline and zircon. Arenite units spatially associated with the siltstone consist of subangular strained quartz and minor chert in a ferruginous clay matrix. Dolomitic siltstone consists of fine-grained micritic carbonate enclosing detrital quartz grains. The carbonate displays millimetre-scale laminations. Outcrops south of North Bore have oolite-like structures, 1.1 to 1.4 mm in diameter, composed of fine dolomite and opaque minerals.

Possible tuffaceous units are present 2 km west-southwest of Cave Hill. They are dark green-grey in colour and have a fine vesicular texture. The vesicles are filled



with opaline or chalcedonic quartz. The matrix consists of glassy material with abundant clays of the illite group. The fine spherulitic appearance is probably the result of devitrification of the glass. The matrix is locally replaced by carbonate.

In the western part of the Yerrida Basin (Plate 1), the Johnson Cairn Formation is dominantly argillaceous, which results in subdued outcrops. The contact with the enclosing units of the Windplain Subgroup is not exposed, but disconformable contacts with the overlying Doolgunna Formation can be seen on DOOLGUNNA (Adamides, 1998). The lower contact with the Juderina Formation is probably transitional. In the northwest, the Johnson Cairn Formation is in faulted contact with rocks of the Bryah Group.

On GLENGARRY rocks of the Johnson Cairn Formation are laminated, argillaceous, purple to grey siltstones, with significant interbedded lithic wacke. Thin beds of dolomite are common. Samples collected from wells consist of greenish-grey, graded, mafic lithic arenite. The main components are plagioclase and K-feldspar, associated with abundant amphibole. Epidote is present in the matrix, may be metamorphic, and is associated with minor muscovite and biotite. Quartz is present in minor amounts, as are sedimentary fragments, dominantly of chert and siltstone. These lithic arenites can be attributed to the rapid erosion of a granite–greenstone-dominated terrain. Carbonate units, mainly dolomite and marl, are present in the east where they are intruded by dolerite.

## Mooloogool Subgroup

The Mooloogool Subgroup conformably overlies the Windplain Subgroup and contains four formations: Thaduna, Doolgunna, Killara, and Maraloou. Sedimentological characteristics suggest that it was deposited in a rift-basin setting (Pirajno et al., 1995, 1996).

The sedimentary rocks of the Thaduna and Doolgunna Formations (conglomerates, turbidite-facies rocks) were deposited in a high-energy environment that indicates an abrupt change from the shallow and mature environment of the Windplain Subgroup. These two formations form a broad northeasterly trending belt around the Goodin Inlier (Fig. 1). The Goodin and Marymia Inliers were the principal source for the sediments of the Thaduna and Doolgunna Formations. The two formations interdigitate and, along with the mafic rocks of the Killara Formation, indicate a complex depositional environment in which sedimentation was taking place at the same time as volcanism. The Doolgunna Formation contains conglomerates, turbidite rocks, and diamictite units that accumulated in a graben-like depository (Doolgunna graben; Pirajno 1996; Pirajno and Occhipinti, 1998). The diamictites are the result of mass-wasting sourced from rocks overlying and including the Goodin Inlier. The Thaduna Formation is a turbiditic succession of coarse to fine wackes, containing lithic fragments of volcanic rocks, shale, and siltstone. The volcanic rocks were sourced from the Archaean greenstones in the Marymia Inlier and from the Killara and Narracoota Formations. The Killara Formation consists of lavas and sills of tholeiitic composition, emplaced in a continental environment.

The Maraloou Formation contains rhythmically laminated siltstone, sulfidic shale, marl, dolostone, and minor chert. The formation is indicative of a deepening of the basin and an anoxic low-energy lacustrine environment.

## Doolgunna Formation

The Doolgunna Formation (Occhipinti et al., 1997; originally ‘Doolgunna Arkose’ of Gee, 1979) is distributed mainly around the Goodin Inlier, except on its northern side where the formation locally interfingers with the Thaduna Formation (see below). Kaolinitic wackes of the Doolgunna Formation and maroon-coloured, ferruginous lithic wackes of the Thaduna Formation interdigitate on THADUNA (Pirajno and Adamides, 1998) and probably on MOUNT BARTLE (Dawes and Pirajno, 1998). The Doolgunna Formation is largely sourced from the Goodin Inlier, based on its distribution around the inlier and the nature of the component clasts. The thickness of the Doolgunna Formation decreases away from the Goodin Inlier.

The lower contact of the Doolgunna Formation with the Johnson Cairn Formation is commonly marked by the first appearance of kaolinitic quartz wacke. The contact is disconformable northwest of the Goodin Inlier and gradational in the areas east of the inlier. On GLENGARRY the lowest part of the Doolgunna Formation above the Johnson Cairn Formation is defined by a sequence of fluvial sandstones and pebble beds. The pebble beds are overlain by diamictite units that define a zone at the boundary with the main arkosic wacke. South of the Goodin Inlier, on MOOLOOGOL, the Doolgunna Formation is an arkosic wacke that appears conformable with the Johnson Cairn Formation. East of the Goodin Inlier, the formation is conformable with the Johnson Cairn Formation and displays interfingering relationships with the Thaduna Formation.

Northwest of the Goodin Inlier, the Doolgunna Formation is faulted against the Karalundi Formation (Bryah Group) along the Goodin Fault (Fig. 1). East of the Goodin Inlier, on THADUNA, the formation is overlain unconformably by siltstones of the Maraloou Formation (Pirajno and Adamides, 1998), with the contact defined by a thin sequence of laminated chert and chert breccia in central THADUNA. On MOOLOOGOL, south of the Goodin Inlier, the formation is intercalated with the Killara Formation and overlain, probably unconformably, by siltstones of the Maraloou Formation.

The basal unit of the formation is probably of fluvial origin, deposited during an initial deltaic period of sedimentation. In the northeastern PART OF GLENGARRY it comprises a sequence of arenites and associated pebble beds. Bands of oligomictic conglomerate are present, almost exclusively comprising vein quartz with clasts up to several centimetres in size. They are subangular to rounded and enclosed in a matrix of medium-grained quartz arenite. Zones of strong silicification and brecciation are associated with arenites and pebble beds, and probably testify to hydrothermal activity associated with faulting.



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**Figure 8. Thick-bedded granite-derived quartz wacke of the Doolgunna Formation, about 4 km east of John Bore**

The Doolgunna Formation is typically an arkosic turbidite sequence of whitish arenaceous wacke beds, commonly averaging 1 m in thickness, but locally up to 3 m thick (Fig. 8). Rocks weather orange-brown and closely resemble granite in their weathering characteristics. The beds consist of upward-fining sequences with evidence of intense scouring in the lower parts, and laminated facies at the upper levels. The basal contacts are marked by lags of pale, argillaceous rip-up clasts and pebbles. Cyclic units are commonly stacked in upward-thinning beds, with broad concave bases suggestive of channelized turbidite flow. Greenish-grey siltstones separate individual beds and these are often scoured out by the subsequent sedimentary units. Angular to subrounded clasts, mainly of quartz and up to several centimetres across, are enclosed in an unsorted kaolinitic-rich matrix. Preserved clasts most commonly consist of quartz and chert; however, Gee (1987) mentioned the isolated preservation of identifiable granite clasts in the area of John Bore. In rare cases, chert containing lath-like pseudomorphs, probably of evaporitic minerals, is also present.

Rocks of the Doolgunna Formation consist of subangular quartz and feldspar grains set in a light-brown kaolinitic matrix. Minor white mica is present, in some cases altered to illite. In the weathered varieties, vermiform kaolinite or illite (or both) replace the feldspars. In the less-weathered samples of the formation, fresh feldspars are abundant, commonly consisting of microcline and orthoclase. Zircon is a common accessory mineral. The lithological character of the assemblages suggests derivation from the erosion of granite basement rocks. This is further supported by the examination of heavy mineral populations, which disclose predominantly euhedral and subhedral zircons, apatite, and tourmaline, in association with titanomagnetite.

A belt of diamictite units occupies a stratigraphic position approximately in the middle of the formation and is particularly well developed from the area 8 km west of Centre Pool Bore to 2 km south-southwest of Mount Leake Bore on DOOLGUNNA (Adamides, 1998). This belt,

which may be up to 300 m thick, includes clasts and blocks, up to several metres in diameter, of banded, microbial chert, laminated quartz arenite, and chert breccia of the Bubble Well Member of the Juderina Formation (Fig. 9). The blocks are enclosed in a white, sheared, silty kaolinitic matrix. This diamictite is interpreted as the result of mass wasting, probably derived from the unroofing of basement and deposited in a deepening trough (Doolgunna trough; Pirajno et al., 1995, 1996). Associated bands of fine-grained granule conglomerate locally exhibit inverse to normal grading, suggesting a genesis by debris-flow processes.

A sequence of thinly bedded, fissile, purple-grey siltstones exposed on THADUNA has been assigned to the Doolgunna Formation because of spatial relationships (Pirajno and Adamides, 1998). The siltstones are in beds 10 to 30 cm thick and show well-developed millimetre-scale parallel laminations and shallow-water ripple cross-laminations. They locally contain ellipsoidal diagenetic ironstone nodules up to 30 cm in diameter. Similar concretions have been described in argillaceous units of the Thaduna Formation by Dawes and Pirajno (1998). A few beds are disturbed by syndepositional faulting.

The Doolgunna Formation shows wide variation in thickness and lithology throughout the Yerrida Basin. It is thickest in the northern part of the Goodin Inlier, where it may be 5 km thick (Gee, 1987). South of the inlier, on MOOLOOGOO (Pirajno et al., 1998b), it is considerably thinner and forms a narrow belt extending for approximately 20 km eastwards from Rainlover Well. At the eastern end of this belt, the formation includes quartz sandstone with minor pebble beds and arkosic wacke, intercalated with dolerite sills (Killara Formation), and is in contact with rocks of the Thaduna Formation. East of the Goodin Inlier, the formation thins to a sequence of kaolinitic wacke and shale. Beds are normally graded, with subangular quartz in a kaolinitic matrix. Coarser pebbly facies are present locally, with subrounded pebbles of quartz and chert infilling channels in the wacke. Individual wacke beds are commonly thin, in the range of 40 to 70 cm, locally thinning to 10 cm.



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**Figure 9. Rounded block of chert breccia in an unsorted matrix of diamictite of the Doolgunna Formation**

## Thaduna Formation

The Thaduna Formation (redefined by Occhipinti et al., 1997) derives its name from the type area at the Thaduna copper mine. It is equivalent to the 'Thaduna Beds' of MacLeod (1970) and the 'Thaduna Greywacke' of Gee (1979, 1987). Outcrops in the Bryah Basin that were previously included in the 'Thaduna Greywacke' are now assigned to the Ravelstone and Narracoota Formations of the Bryah Group (Occhipinti et al., 1997; Pirajno et al., 2000). In areas north and east of the Goodin Inlier, the Thaduna Formation forms the base of the Mooloogool Subgroup, where it conformably overlies the Johnson Cairn Formation. Its thickest development is in the area of the Thaduna and Green Dragon copper mines on MARYMIA (Bagas, 1998). Southwest of the Thaduna mine it passes, in an interfingering relationship, into the thick turbidite wedge of the Doolgunna Formation (Adamides, 1998). In the area of MOUNT BARTLE the formation is intercalated with the mafic rocks of the Killara Formation (Dawes and Pirajno, 1998), whereas similar intercalations of lithic wacke and mafic rocks are noted on the southern margin of THADUNA (Pirajno and Adamides, 1998).

These relationships suggest contemporaneous sedimentation with the Doolgunna and Killara Formations. The interfingering relationships in the lateral sense are repeated in the vertical sense, with passage of the predominantly lithic wacke of the Thaduna Formation upwards into the granite-derived wacke of the Doolgunna Formation.

The Thaduna Formation is predominantly a sequence of lithic sandstone, quartz wacke with intercalated siltstone and shale, and subordinate dolomite. Blockley (1968), based on surface geology and drilling information at the Thaduna mine, subdivided the formation at the type area into two siltstone and two wacke units. The lower siltstone unit, of undetermined thickness, is overlain by a coarsening-upward greywacke unit (the lower greywacke), estimated to be 750 m thick and composed of interbedded coarse-, medium-, and fine-grained lithic wacke. The upper siltstone member is approximately 60 m thick and overlain by the upper greywacke unit, about 90 m thick. Lithologically the two greywacke units are almost identical, varying only in the higher proportion of shale associated with the lower greywacke.

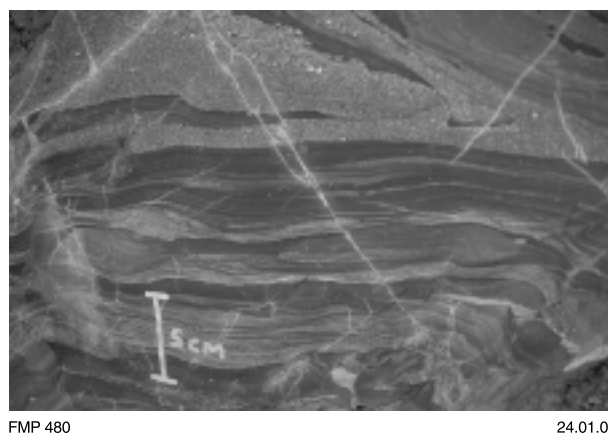
The lithic sandstone commonly comprises beds, averaging 1 to 2 m in thickness, of grey hard rock, which in the more even-grained varieties bears a superficial resemblance to dolerite. Elsewhere, outcrops are deeply weathered and have a characteristic red-brown hematitic staining, with primary mineralogy mainly destroyed. Individual wacke beds commonly have a scoured lower contact with the underlying shale and display typical features of a Bouma sequence (Bouma, 1962). Associated siltstones are thinly bedded and commonly parallel laminated. They typically show a purple colouration as a result of the abundance of finely divided iron oxides.

Lithic sandstone from the type area is composed of a mixture of mainly angular and sparse rounded quartz, abundant potash feldspar (including microcline), albitized plagioclase, epidote, and less abundant siltstone and sparse

carbonate grains. These are set in a fine-grained unsorted matrix, which is commonly extensively chloritized. Titanomagnetite, with well-developed lamellae of ilmenite, is the main opaque mineral. Chlorite (apart from its presence as separate clasts) with blue and purple birefringence is also present in the matrix as a new phase or a replacement of feldspar. Epidote, locally an important constituent, is commonly detrital. However, both chlorite and epidote also replace siltstone clasts, probably as a result of hydrothermal alteration. Volcanic-derived components typically include numerous clasts of tholeiitic basalt containing small plagioclase laths set in a chloritic matrix.

Away from the type area, on DOOLGUNNA (Adamides, 1998) and THADUNA (Pirajno and Adamides, 1998), the formation is a sequence of purple-grey weathered litharenite interbedded with thin, sandy, and silty units with parallel and convolute laminations (Fig. 10). Both singly and multiply graded layers are present. They commonly include lithic clasts up to several centimetres across mixed with abundant rip-up clasts. These rocks are characterized by abundant fine-grained iron hydroxides, imparting a distinctive red-brown colour. They are composed predominantly of subrounded quartz, subordinate fine-grained quartzite fragments, minor feldspar, locally granophyric siltstone fragments, and angular clasts of opaque minerals. The majority of feldspar is converted to vermiform kaolinite, associated with minor illite. Lithic fragments are rarely preserved, being mostly altered to clays. The matrix is predominantly composed of kaolinite, which is in the form of acicular aggregates, probably pseudomorphing chlorite.

Elsewhere, the formation shows widespread interdigitation with both the Doolgunna and Killara Formations. On MOUNT BARTLE (Dawes and Pirajno, 1998), the lower part of the Thaduna Formation is exposed around the Diamond Well anticline. In this area it is intercalated with rocks of both the Doolgunna and Killara Formations and includes pale-coloured litharenites and associated argillaceous rock types that form beds 15 cm to 1 m thick.



**Figure 10.** Soft-sediment deformation structures in rocks of the Thaduna Formation, about 8 km northeast of No. 8 Bore

The wacke beds show typical turbidite features, with variations across the beds from a basal granulestone unit through sandstone to an upper siltstone unit. Scour-and-fill structures are present in the base of the thicker units, with a conglomeratic lag of rounded quartz pebbles and a common easterly orientation of scour channels. The wackes are composed of variable amounts of angular to subrounded quartz, associated with chert and feldspar. In places, chert forms an important component of the rock.

The lithic wacke typically forms beds varying in thickness from a few centimetres up to 2 m, and is intercalated with finely laminated siltstone. The wacke contains an abundance of sedimentary structures (cross-bedding, scours, slumps) consistent with a turbidite origin. Complete Bouma sequences (Bouma, 1962) are observed in some of the more complete turbidite units. Angular rip-up clasts of siltstone or wacke are abundant, particularly in the lower parts of the wacke beds, and these vary in size upwards from a few millimetres to angular blocks several centimetres in size.

The siltstones interbedded with the wacke are parallel-laminated on a millimetre scale, and form beds averaging 10 cm in thickness (Fig. 11). They commonly show parallel or small-scale cross-laminations and fine slump structures. Flame structures are also common where these siltstone are interbedded with lithic wacke (Fig. 12). Brecciation of the substrate and incorporation as rip-up clasts in lithic wacke is consistent with turbiditic activity.

In the upper levels of the Thaduna Formation on MOUNT BARTLE, a subfacies of the Thaduna Formation wacke is a mixed sequence of well-bedded quartzose and feldspathic litharenite and wacke, locally subarkosic, associated with fine-grained laminated siltstones and shales. Flattened, discoidal, or ellipsoidal diagenetic ferruginous concretions, up to 80 by 30 cm, are locally present in the siltstones. Minor conglomerate is locally associated with this unit, reaching a thickness of up to 40 cm and composed of predominantly subrounded and rounded pebbles and cobbles set in a matrix of ferruginous



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**Figure 11. Laminated turbiditic siltstone of the Thaduna Formation**



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**Figure 12. Flame structures in lithic wacke of the Thaduna Formation**

sandstone. Clast types in the conglomerate include grey chert, ferruginous arenite, and pale feldspathic sandstone.

An outcrop on the southeastern side of the Goodin Inlier, approximately 3.5 km north of Divide Bore (Plate 1; Pirajno et al., 1998b) consists of turbiditic quartz wacke, siltstone, laminated volcanoclastic mudstone, and thin beds of grey volcanic ash. The volcanoclastic rock contains quartz, biotite, sericite, chalcedony, and kaolinitic clays replacing crystal fragments and lithic fragments of basaltic scoria (Fig. 13). Clay-replaced particles are either pyroclasts or crystals. The outcrop is interpreted as mass-flow deposits deposited in a trough formed by local uplift and subsidence during volcano-sedimentary processes.



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**Figure 13. Block of volcanic scoria in turbidite rocks of the Thaduna Formation (after Pirajno et al., 1998b)**

## Killara Formation

The Killara Formation was originally part of the 'dolerite sills' of Elias et al. (1982). Subsequently, all mafic rocks of the former 'Glengarry Group' (Bryah and Yerrida Groups) were included in the 'Narracoota Volcanics' (Gee, 1987; Gee and Grey, 1993). The 'Narracoota Volcanics' have since been redefined (Occhipinti et al., 1997) and subdivided into the Narracoota Formation in the Bryah Group (Pirajno et al., 1998c) and Killara Formation in the Yerrida Group. Details of the geology, petrography, and geochemistry of the Killara Formation have been reported by Dawes and Pirajno (1998) and Pirajno et al. (1998c).

The Killara Formation outcrops in the southern, eastern, and southeastern parts of the Yerrida Basin. To the east of the Goodin Inlier (Fig. 1), units of the Killara Formation interdigitate with the Johnson Cairn, Doolgunna, and Thaduna Formations. The formation also interdigitates with the base of, and is transitional to, the overlying Maraloou Formation.

The Killara Formation forms a T-shaped zone across the central and eastern parts of the Yerrida Basin (Plate 1 and Fig. 1). The stem of the 'T' trends northwest and is aligned with Archaean greenstone units, and the top of the 'T' has an east-northeast to northeast trend parallel to the Goodin Fault. The significance of the T-shape is discussed in **Basin development and tectonic evolution**. The stratigraphic relationships of the Killara Formation with other units of the Yerrida Group are shown in Figure 2.

The Killara Formation consists of subalkaline intrusive and extrusive rocks, with minor intercalations of chertified volcanoclastic rocks. The thickness of the Killara Formation is uncertain, but is estimated to be in the order of 1000 m (Pirajno et al., 1995). The mafic rocks are commonly unmetamorphosed, and flat lying or shallow dipping. They have tholeiitic to calc-alkaline basaltic and basaltic andesite compositions, and were emplaced as subaerial and subaqueous lava flows, intrusive sheets, sills, and dykes (Pirajno et al., 1998c).

An important component of the Killara Formation is the Bartle Member, consisting of chertified microbial laminites with barite and anhydrite nodules, massive chert, and chert breccia. These units are stratigraphically at the top of the Killara Formation and represent the end-phase of volcanic activity. Relic textures in the Bartle Member cherts suggest that precursor rock types included volcanoclastics, hot spring-related chemical sedimentary rocks, and evaporites (Pirajno and Grey, 1997; Dawes and Pirajno, 1998).

The Killara Formation is interpreted to represent continental volcanism associated with the rifting phase of the Yerrida Basin. Fifteen individual lava flows are present in a 90 m-thick section of drillcore (see below) from an area 3 km east of North Bore, indicating a high rate of eruption. Two km north of Desert Well, a diamond drillhole (KDD 1; Bromley and Cull, 1985) intersected an undisturbed, flat-lying succession of tholeiitic basalt pillow lavas and dolerite sills, from about 319 m below the surface to the final depth of 503 m (Fig. 14). They

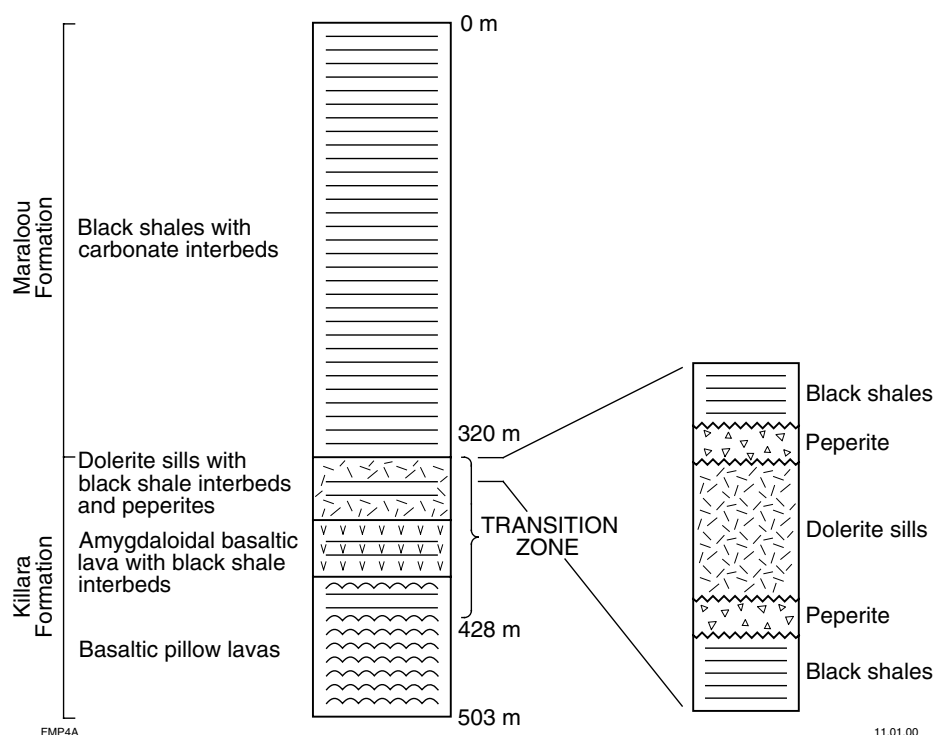


Figure 14. Idealized stratigraphy of the Killara and Maraloou Formations in drillhole KDD 1 (after Pirajno et al., 1998b)

underlie a succession of siltstone and pyritic black shales of the Maraloou Formation. There is a 108 m-thick transition zone between the siltstone – black shale succession and the pillow lavas. This is characterized by intercalated thin beds of shale, doleritic sills, and amygdaloidal lavas. Peperite margins in the contact zones between the igneous material and the sedimentary rocks suggest that the mafic magma intruded or was erupted on wet, poorly consolidated sediments (Pirajno et al., 1995).

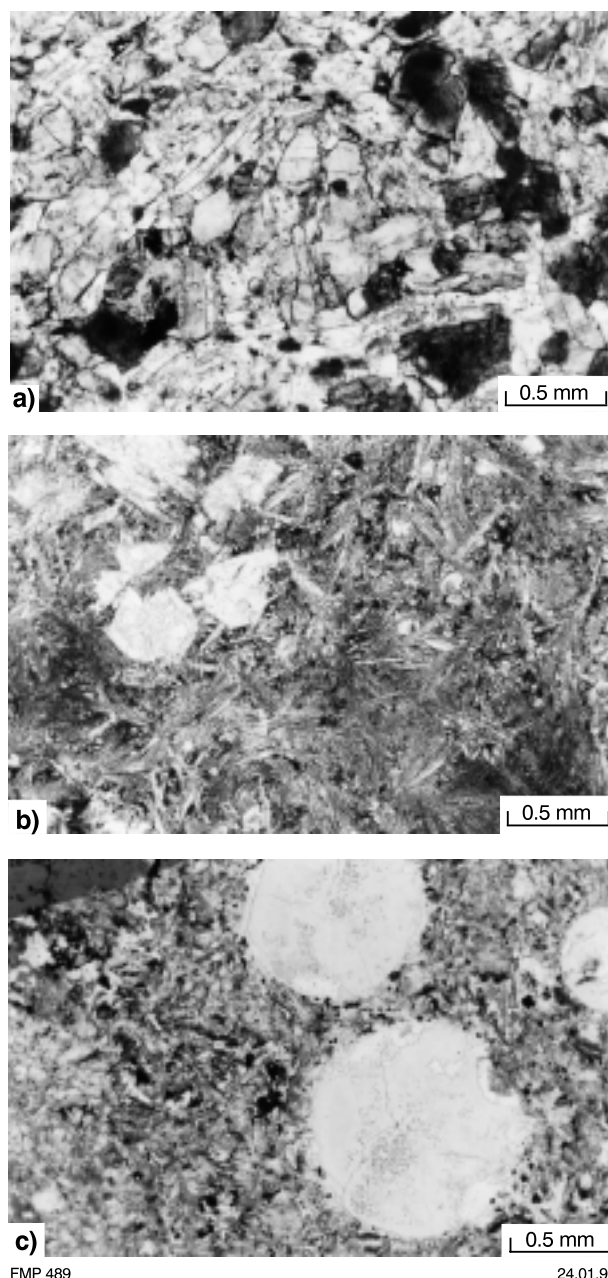
### Mafic intrusive rocks

Mafic intrusive rocks are dark grey to greenish grey, commonly weathering brown to reddish brown. Grain size varies from fine to coarse, but the vast majority of outcrops are composed of homogeneous dolerite. Gradations to aphanitic material presumably indicate proximity to contacts, but no chilled margins have been observed. Doleritic bodies tend to be well jointed, and spheroidal weathering is very common

The bulk of the mafic rocks are ophitic to subophitic augite dolerite (Fig. 15a), with or without orthopyroxene. Some sills are of hypersthene dolerite. Plagioclase is labradorite in composition (optical determinations range from An<sub>55</sub> to An<sub>70</sub>). Accessory quartz may be present, in places with chlorite and epidote. Main opaque minerals are leucoxene and ilmenite; the latter commonly in skeletal form. Dolerite rocks show variable degrees of alteration and epidotization. Plagioclase has commonly been saussuritized, and the pyroxene serpentinized. Dolerite rocks are quartz, albite, diopside, and hypersthene normative.

An east-northeasterly trending dolerite – tholeiitic basalt complex, about 23 km long and 200 to 300 m thick, is present in the southwestern Yerrida Basin, on MOOLOOGOL. The dolerites are locally intercalated with thin units of amygdaloidal tholeiitic basalt. Dolerite is commonly well jointed, has a characteristic spheroidal weathering, and consists of clinopyroxene and labradorite (An<sub>55-65</sub>) crystals set in a cryptocrystalline to holocrystalline groundmass, which also contains disseminated titanite partly altered to leucoxene, minor chlorite, and carbonate. Dolerite sills intrude the Johnson Cairn and Doolgunna Formations north and northeast of this belt. Minor sills intruding the Johnson Cairn Formation are present west of Mooloogool Homestead. A series of dolerite sills are intercalated with argillaceous siltstone of the Johnson Cairn Formation on MOOLOOGOL, in the higher part of this unit up to the contact with the Doolgunna Formation. Textures of the dolerite vary from fine- to medium-grained holocrystalline to ophitic. Hornblende, clinopyroxene, and plagioclase are the main component minerals, with the amphibole in most cases almost totally replacing the clinopyroxene. Granophyric textures between quartz and plagioclase are locally well developed. Chlorite, clinozoisite, epidote, and titanite are present as alteration minerals. The chlorite–clinozoisite assemblage replaces plagioclase along fractures, in the form of microgranular aggregates. Epidote is euhedral against the enclosing amphibole.

The dolerite–tholeiitic complex and adjacent dolerite sills are aligned east-northeast to northeast and parallel to



**Figure 15.** Killara Formation mafic rocks in plane polarized light: a) fresh clinopyroxene crystals and plagioclase laths of a typical dolerite; b) basalt with feathery microcrystalline groundmass with augite and labradorite microphenocrysts; c) vesicular, fine-grained tholeiitic basalt, vesicles contain chlorite and calcite

the Goodin Fault (Plate 1). Two volcanic centres are also present in this zone (3 km south of North Bore and 7 km northeast of Yerrida Spring; Plate 1) and they are discussed more fully below.

Halfway between North Bore and North Well, three diamond drillholes (GD-1, GD-2, and GD-3; Guj and McIntosh, 1984) intersected an 80 to 90 m-thick gabbroic sill, dipping about 60° to the south. The sill was intruded between layers of pyritic black shale of the Johnson Cairn Formation (see **Mineralization**). A well-developed zone

of hydrothermal alteration along the footwall of the sill is associated with weak sulfide disseminations. This zone of alteration and mineralization correlates with a surface gossan (Guj and McIntosh, 1984), which is further discussed in **Mineralization**. A fourth diamond drillhole (GD-4; Guj and McIntosh, 1984), collared in dolerite about 4.5 km east-southeast of the first three, intersected a succession of 15 aphyric, vesicular, tholeiitic basalt lava flows, with minor interflow cherty sedimentary material between 72 and 162 m. Thus, from outcrop data and the four diamond drillholes, the entire succession consists of, from top to bottom, dolerite, tholeiitic basalt lava flows, black shale, gabbroic sill with associated hydrothermal alteration, black shale with intercalated thin tholeiitic lava, shale, and another gabbroic sill.

On MOUNT BARTLE, sills of dolerite and, more rarely, gabbro form conspicuous outcrops. Near Bobs Bore (Plate 1), a rounded dolerite mass intruded the Thaduna Formation, and may represent a discordant intrusive. A southeasterly dipping body of dolerite and gabbro, perhaps 200 m thick, is exposed north of Diamond Well Homestead. The dominant rock type is a medium-grained dolerite, but fine-grained zones may indicate a composite or differentiated intrusion. Pods and veins of pegmatoid-like segregations are also present. The dolerite contains clinopyroxene, plagioclase laths (0.2 – 1 mm long), and interstitial quartz and chlorite; leucoxene is an accessory mineral. A medium- to coarse-grained variety has fresh plagioclase laths up to 1 mm, with serpentized hypersthene phenocrysts 1.5 to 2 mm across. The pegmatoid-like material is essentially a prehnite–quartz–pyroxene rock. Massive quartz, spherulitic prehnite, and augite are the main minerals, with accessory chlorite, sericite, and carbonate. Quartz and prehnite replace an original pyroxene–plagioclase assemblage, and there is relict pyroxene in some samples.

On CUNYU the Killara Formation consists mostly of dolerite sills, which intrude the arenite units of the Juderina Formation, although fine-grained, basaltic flow units predominate in the upper parts of the formation. Dolerite forms thick sills (up to 150 m) at three stratigraphic levels in the Juderina Formation. The distribution of the dolerite sills appears to be partly controlled by siltstone units, in that intrusion preferentially occurred along their contacts with more competent arenite beds. Dolerite is dark grey to black, shows blocky to spheroidal weathering, and typically forms resistant ridges. It is locally microporphyrritic and consists of fresh clinopyroxene, commonly with polysynthetic twinning, and plagioclase locally displaying normal igneous zoning. The composition of the plagioclase ranges from andesine to labradorite. Two types of pyroxene are locally present — weakly pleochroic orthopyroxene, which is commonly serpentized, and fresh and colourless pyroxene, probably augite. Interstitial granophyric intergrowths of quartz and feldspar are well developed. The opaque mineral in the dolerite is titanomagnetite, which is variably altered to leucoxene and displays trellis-type exsolution lamellae of ilmenite. Pegmatitic segregations are locally present and the rock is locally veined by a quartz–epidote assemblage.

The largest of the dolerite sills, informally called the Cunyu sill, outcrops west of Mount Alice in the southern

part of CUNYU. The sill extends in a northwesterly direction for 18 km, and is 30 to 150 m thick. The upper and lower contacts of the sill with the Juderina Formation are marked by development of peperite. Peperitic dolerite is distinguished by a high content of country-rock fragments, hydrothermal alteration, interstitial devitrified glass, quench textures, and weak disseminations of sulfide mineralization (mainly pyrrhotite and pyrite). In these zones, pyrrhotite typically fills cavities and is rimmed by zeolite minerals and calcite. The Cunyu sill has a higher magnetic susceptibility at its upper and lower contacts relative to its central parts. These variations can be attributed to the effects of hydrothermal alteration during peperite development.

The Cunyu sill typically contains augite and cloudy plagioclase laths (labradorite), with prehnite, pumpellyite, calcite, palagonite, zeolite, and chlorite as alteration minerals, disseminated skeletal ilmenite, leucoxene, and sulfides. The sulfides tend to form small (<0.01 to 0.02 mm) irregular blebs and include pyrite, hexagonal pyrrhotite (non-magnetic), smythite ( $(\text{Fe,Ni})_9\text{S}_{11}$ ), and occasional chalcopyrite. A highly reflective sulfide (probably a lead arsenide) is present as submicroscopic inclusions in pyrrhotite.

### **Mafic extrusive rocks**

Mafic extrusive rocks are fine-grained, aphanitic, commonly vesicular clinopyroxene-bearing tholeiitic basalts. Vesicles range in size from less than 1 mm up to 3 mm. Where abundant, they produce a spotted to speckled texture. The basaltic lavas are locally associated with tuffaceous rocks, which are commonly silicified and tend to be laminated, but lighter in colour (see below).

The basalts are typically poorly exposed; the outcrops are commonly no more than rubble-covered ground. A prominent feature is the presence of druse quartz with varieties of chalcedony such as chrysoprase. In highly ferruginized basalt, igneous texture can no longer be recognized and the rocks are composed of hydrated iron oxides, clay, quartz, and relict feldspar, with or without carbonate. In most cases, the tholeiitic basalts weather to a brown-black colour, and much of the outcrop has a hummocky appearance, locally resembling pillows.

Tholeiitic basalt is commonly aphyric, or less commonly microporphyritic or glomeroporphyritic, and contains normative albite, diopside, hypersthene, minor quartz, and olivine. Augite is commonly present both as phenocrysts and in the groundmass. In some porphyritic basalts, scattered augite phenocrysts up to 1.5 mm in size and plagioclase laths up to 3 mm are set in a very fine grained feathery groundmass composed of clinopyroxene, plagioclase, and devitrified glass (Fig. 15b). Plagioclase varies from fresh to completely altered (clay minerals and chlorite). The main accessory mineral is ilmenite, which is in various stages of alteration to leucoxene. Pumpellyite is present in some rocks, implying very low grades of metamorphism, possibly by burial alone. Chlorite is partly a replacement of feldspar and commonly present as discrete interstitial patches, as well as vesicle infillings. Quartz, prehnite, zeolite, chlorite, and carbonate are the main minerals infilling vesicles



(Fig. 15c). Carbonate is most common, but various combinations of infillings include prehnite–quartz, quartz–zeolite, and quartz–calcite–zeolite. Coalesced vesicles have been noted. In some samples two types of vesicles are present: either chert-rimmed and calcite–prehnite-filled or entirely filled with glassy material.

Aphyric varieties of basalt have a fine-grained, variolitic or intersertal to hyalopilitic texture, with plagioclase microlites, augite grains, and minor amounts of quartz. Alteration phases include chlorite, epidote, prehnite, calcite, and chlorite. In places, plagioclase also forms unusual shard-like or sinuous veinlet-like shapes, which could be quenched melts. The groundmass is brown, greenish to dark glass with abundant disseminated rutile granules. Amygdales are usually filled with calcite, chlorite, epidote, quartz, and, in places, feldspar or granophyric quartz–feldspar. In other cases, vesicles contain chlorite or (from rim to core) calcite, chlorite, and zeolite (?stilbite).

The microporphyritic and glomeroporphyritic varieties are characterized by microphenocrysts of plagioclase, clinopyroxene or amphibole in a variolitic matrix composed of randomly oriented plagioclase and feathery clinopyroxene crystals, with disseminated rutile granules. Plagioclase laths are about 0.6 mm long, associated with amphibole, and form clusters set in a fine groundmass of fresh plagioclase, about 0.2 mm long, and dominant actinolitic amphibole. The plagioclase laths are either partly albitized or show a fine pervasive alteration to chlorite and epidote grains. Vesicles are rounded, about 1 mm in diameter, and completely filled by quartz, clinozoisite, and minor biotite. Vein minerals include quartz and clinozoisite.

### **Volcaniclastic rocks**

Volcaniclastic deposits are uncommon. There is a possible volcanic centre, approximately 3 km south of North Bore, on MOOLOOGUOL, which consists of widespread volcanic breccia (possibly a vent breccia) surrounded by pods of laminated silicified rock. The laminae of the silicified rock are composed of quartz grains, microcrystalline quartz, disseminated actinolite needles, and crystal fragments tentatively identified as axinite (a boron-bearing aluminosilicate). Spherulites and shard-like shapes are also present. Similar rock types are present in drillholes 3.5 km northeast of the volcanic centre. The association of this rock with a volcanic breccia and its textural features, suggest that the precursor lithology may have been either a pyroclastic surge deposit or a chemical precipitate at the site of hydrothermal discharge. Another interpreted volcanic centre, with similar features, is located about 7 km northeast of Yerrida Spring (Plate 1). These volcanic centres are situated on the prominent east-northeasterly to northeasterly trending structure, along which dolerite–tholeiitic complexes are emplaced (Plate 1 and Fig. 1).

Many outcrops of volcaniclastic rock are too small to show on the geological map. These rocks are laminated chertified units consisting of granoblastic aggregates of quartz, microcline, and albite, overprinted by brown biotite and containing lithic fragments. In other instances, the rock is composed of an equigranular, lobate polygonal

aggregate of quartz, albite, microcline, and disseminated rutile grains. These units are interpreted as fine volcanoclastic turbidites, derived from the erosion of volcanic rocks and then thermally metamorphosed (quartz–biotite hornfels) by subsequent eruptions of mafic lavas.

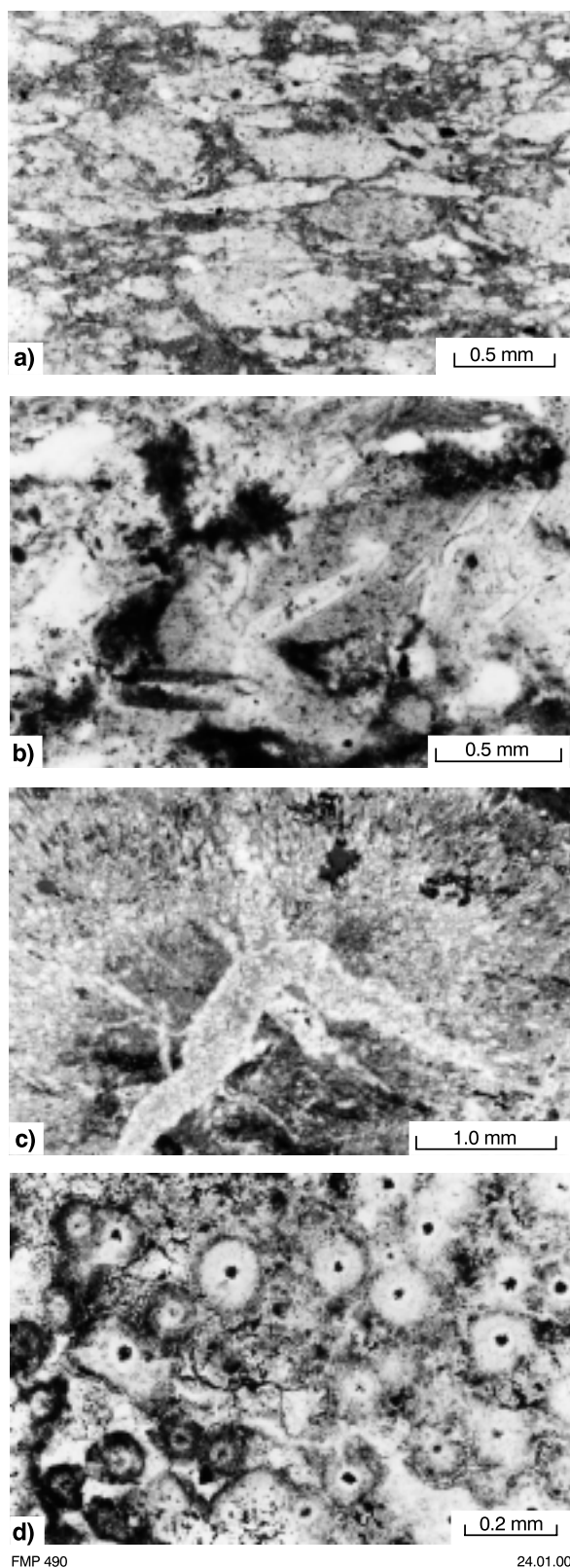
On CUNYU, very fine grained, pale-green, and locally spotted, laminated chert-like rocks form narrow (5–100 cm-wide) subparallel 50 to 60 m-long bands in dolerite. The dolerite enclosing these bands is fractured and veined with the same material. Good exposures of these cherty bands are present near the junction of the Wiluna North road with the Canning Stock Route. These rocks consist of a mosaic of lobate quartz and prismatic clinozoisite, with a distinct granular texture. Disseminated epidote porphyroblasts (?pistacite) impart a spotted appearance, and crosscutting veinlets of quartz and clinozoisite are also present. These rocks can be classed as epidosite. They represent either a thermally metamorphosed volcanoclastic layer or sites of a hydrothermal reaction zone within which seawater, heated from underlying mafic melts, has reacted with the surrounding rocks to form epidote and quartz at the expense of calcic plagioclase.

### **Bartle Member**

The ‘chert and chert breccia’ mapped as part of the Maraloou Formation (Elias et al., 1982), and described by Gee and Grey (1993) as ‘cherty interflow sediments’ of the ‘Narracoota Volcanics’, are now assigned to the Bartle Member. The member outcrops in a northwesterly trending arcuate band in the eastern part of the Yerrida Basin (Plate 1). The type area for the member is immediately northwest and east of White Well. Locally, the member is interbedded with the basaltic rocks. It is overlain by the deeper water argillaceous sedimentary rocks of the Maraloou Formation, along what is interpreted to be a regionally conformable and locally interdigitating zone. Although the presence of fine-grained clastic rocks interbedded with cherts suggests an association with the Maraloou Formation, field relations justify its assignment to the Killara Formation. The Bartle Member consists of massive chert, chert breccia, laminated chert, and chertified sedimentary rocks. Chertification is pervasive, and preserves a range of sedimentary structures and relict textures, including a few that are interpreted to be of pyroclastic origin. The thickness of the member is uncertain, but regionally it is probably between a few metres and 30 m thick. The most continuous sections expose less than 5 m of strata.

Rocks of the Bartle Member contain round to angular chert clasts, 0.2 to 1 mm in size, of chalcedonic quartz, chlorite, iron oxides, kaolinite, and, locally, garnet. Despite the pervasive chertification, petrographic studies reveal a variety of textures that suggest fine, welded pyroclastic material (e.g. flaser texture, cusped glass shards, and flattened ash particles; Fig. 16a), carbonate allochems, kaolinized (scanning electron microscope analysis), bladed, rosette-like or stellate crystal pseudomorphs (probably after sulfate, such as gypsum or anhydrite) in chert laminites, and silica-pseudomorphed nodules (Fig. 16b). One sample of laminated chert displays





**Figure 16.** Bartle Member rocks (after Dawes and Pirajno, 1998): a) possible pyroclastic texture in chert (plane polarized light); b) euhedral crystals, probably of gypsum, pseudomorphed by fine silica (plane polarized light); c) portion of nodule (possibly anhydrite) with septarian cracks filled with chalcedonic quartz (crossed polars); d) silica-iron oxide spherules (0.02 - 0.1 mm), possibly biogenic (plane polarized light)

septarian nodular concretions up to 5 mm in diameter (Fig. 16c). These nodules are chertified, with the septarian cracks filled with chalcedonic quartz. Relict inclusions of low-birefringence minerals suggest that these bodies may have been gypsum or anhydrite nodules. Elsewhere, zeolite aggregates are common, and in one sample thomsonite ( $\text{NaCa}_2\text{Al}_5(\text{SiO}_4)_5 \cdot 6\text{H}_2\text{O}$ ) was tentatively identified. A late phase of chalcedonic quartz is almost ubiquitous. This chalcedony is mainly present as cementing material to angular chert clasts (brecciated chert). The chalcedony is in turn overprinted by euhedral (oxidized) pyrite crystals, and cut by fine quartz veinlets. Some samples, contain garnet (1 mm across), in part replaced by late chalcedony. These same samples also contain curious globules of silica with iron oxide cores, resembling organic cell-like structures (Fig. 16d). In other instances, disseminated blebs or round to prismatic bodies (0.2 to 1.6 mm in size) of brown, unidentifiable material are surrounded by iron oxide spherules (0.012 to 0.014 mm).

Many outcrops of the Bartle Member have significant amounts of plate-like quartz with abundant superficial moulds, possibly after calcite crystals. This quartz is from millimetre scale up to 5 cm, and is also present as blocks that show 'nail-hole-like' and 'nail-like' structures. This quartz morphology is present across a very wide area of poor outcrop near the base of the member. These quartz-rich units appear to form irregular bedding-parallel bands and lenses up to 20 cm thick, and could have been produced either by siliceous replacement of evaporitic minerals or chemical precipitates.

Large, dark-grey granular chert boulders, some over a metre across, within hummocky stratified chert approximately 1 km east of White Well may be a debris-flow deposit. An outcrop of grey chert 7.5 km north of No. 1 Bore on CUNYU shows contorted laminae, suggesting some syndepositional deformation. Cavities in the chert are coated with botryoidal hematite and radiating, spherulitic forms are present in the body of the chert. Samples from this unit contain abundant globular structures, 20–50  $\mu\text{m}$  in diameter, composed of iron hydroxides. Associated with these features are rosettes of radially arranged rhomb-shaped crystals (probably dolomite, now replaced by quartz), with interstices filled with radiating chalcedony. These features suggest silicification of a carbonate rock. Chalcedonic quartz forms spherulites, within which are submicroscopic spheroids approximately 10  $\mu\text{m}$  in diameter.

Protoliths of the Bartle Member may have included carbonate rocks, fine-grained pyroclastic rocks, hot spring deposits, and evaporites. Bedding surfaces with polygonal dessication cracks in laminated cherts indicate emergence and desiccation of ash-rich muds, and millimetre-scale silica-pseudomorphed gypsum concretions and radial fibrous crystal growths of the sodic zeolite thomsonite indicate possible evaporitic conditions. Locally, hot springs may have given rise to algal colonies and precipitated sinter-like deposits (now chalcedonic chert with iron-oxide spherules), some of which contain anomalous gold (Pirajno and Grey, 1997; see **Geochemistry of the Killara Formation**).

The general association of the above features suggest that the unit was formed in an environment of playa lake, associated with alkaline hot springs. A characteristic of salt lake environments is the continuum and diversity of depositional facies, so that only end-members can effectively be recognized. A modern analogue of this environment may be the present-day Afar region in northeast Africa or the East African Rift Valley alkaline lakes, such as the ephemeral Lake Magadi, where hydrous sodium silicates precipitate and are later replaced by microcrystalline silica or chert (Pirajno and Grey, 1997; Eugster, 1986).

Deposition of the Bartle Member rocks occurred at the end of a phase of volcanism (Killara Formation) and this was followed by accumulation of deeper basinal carbonaceous argillites of the Maraloou Formation under anoxic conditions.

### Geochemistry of the Killara Formation

Major- and trace-element, including rare earth element (REE), data from whole-rock analyses of metabasite rocks are on the accompanying disk. Representative analyses are presented in Tables 1 and 2. Major elements were quantified using x-ray fluorescence (XRF), following incorporation of the sample into a borate glass disk, or a pressed powder using a PVA solution as a binder. Cobalt, chromium, copper, nickel, scandium, vanadium, and zinc were determined by inductively coupled plasma atomic emission spectrometry (ICP-AES), whereas REE were determined by inductively coupled plasma mass spectrometry (ICP-MS).

In the discussion below, mafic extrusive and intrusive rocks are treated as one rock type because the tholeiitic basalt and the dolerite differ principally in grain size and texture.

The mafic rocks of the Killara Formation show a very uniform composition with a restricted range of  $\text{SiO}_2$  content (47.1 to 59.8 wt%; mean 51.79 wt%); mean of  $\text{MgO}$  is 6.23 wt% (range 2.36 to 8.91 wt%), and of  $\text{FeO}$  is 10.79 wt% (range 7.80 to 13.86 wt%). Means of selected trace elements are: 269 ppm for Ba (range 82 to 1404 ppm), 18 ppm for Y (range 5 to 43 ppm), 79 ppm for Zr (range 18 to 223 ppm), 5 ppm for Nb (range 0.8 to 12 ppm), 75 ppm for Ni (range 12 to 158 ppm), 116 ppm for Cr (range 16 to 312 ppm), and 8.6 ppb for Au (range 2 to 30 ppb). The average CIPW norm of the mafic rocks is: 7.5 for quartz, 16.4 for albite, 28.4 for anorthite, 22.6 for diopside, 17.2 for hypersthene, 3 for magnetite, and 1.8 for ilmenite. The magnesium number ( $\text{Mg\#}$ ; defined as  $\text{MgO}/(\text{MgO} + \text{FeO}^{2+}) \times 100$ ) ranges from 32 to 60 (compared to  $\text{Mg\#}$  of 50 to 82 of the Narracoota Formation; Pirajno and Davy, 1996).

Based on the total alkali – silica diagram (Le Maitre, 1989), mafic rocks of the Killara Formation range from basaltic to basalt andesite (Fig. 17). The mafic dykes that intrude the Goodin Inlier are indistinguishable from the Killara rocks and it is possible that they are cogenetic.

In terms of trace-element and REE abundances, the rocks of the Killara Formation are different from the

Narracoota Formation of the Bryah Basin, although overall chondrite or primitive mantle-normalized patterns show the same pattern (Pirajno and Davy, 1996; Pirajno et al., 1995). This led Pirajno et al. (1995) to suggest the presence of two mafic magmatic provinces in the region (Pirajno and Davy, 1996; Pirajno et al., 1998c). A Jensen (1976) cationic plot (Fig. 18) shows that the volcanic rocks of the Killara Formation range from high-Fe tholeiites (HFT) to high-Mg tholeiites (HMT), whereas the Narracoota Formation contains predominantly HMTs. Figure 19a shows trends of the incompatible elements Zr and Ti for the Killara and Narracoota Formations. A component of the latter, tholeiitic hyaloclastite rocks, occupies a field between the Narracoota mid-ocean ridge basalt (MORB)-like tholeiites and Killara Formation tholeiites. Pirajno and Occhipinti (1998) suggested that the tholeiitic hyaloclastites of the Narracoota Formation were erupted on the rifted margin of continental crust, and therefore their chemistry is transitional to the tholeiites of the Killara Formation, which are considered to be of continental affinity (see below). A similar transition to Fe-rich tholeiitic magmatism is recorded in the Palaeoproterozoic volcano-sedimentary succession that overlies the Archaean basement in the Fennoscandian Shield (Nykänen et al., 1994). Another interesting aspect of the Killara (and Narracoota) Formation mafic rocks is that they are strongly depleted in base metals (Cu, Ni, Zn, Pb) and Cr (Fig. 19b). A possible explanation of this feature is that the magma was depleted in metallic elements due to contamination with S-rich crustal materials. Sulfur saturation followed allowing precipitation of sulfides, which depleted the original magma in metallic elements. This is the model proposed by Naldrett (1989) to explain the Noril'sk-type Cu–Ni–PGE (platinum-group element) deposits in Russia. This feature has important implications for the prospectivity of the Killara Formation as a possible host to Ni–Cu sulfides.

The tholeiitic trend of the Killara Formation is shown in Figure 20, where the Fe–Mg-rich end of a tholeiitic fractionation series is dominant. Multi-element plots (Figs 21 and 22) indicate that the mafic rocks of the Killara Formation are enriched in the more incompatible elements 10 to 100 times relative to N-type MORB, but only one to 10 times when normalized to continental crust. The nearly flat pattern of the latter implies contamination with crustal material. The negative Nb anomaly is a characteristic of continental flood basalts (Wilson, 1989; Grisel et al., 1997).

The Killara Formation has low chondrite-normalized REE abundances, with a slight light rare earth element (LREE) enrichment and positive Eu anomalies (Fig. 23; average  $\text{La}/\text{Yb}_{\text{CN}}$  is 3.36 and  $\text{Eu}/\text{Eu}^*_{\text{CN}}$  is 1.47). The slight enrichment in the LREE (La, Ce, Pr, Nd, and Sm) is again suggestive of crustal contamination, or an enriched mantle source (Fig. 23). This LREE enrichment of the Killara Formation mafic rocks compares well with the continental Fe-rich tholeiites of the Fennoscandian Palaeoproterozoic rocks (Nykänen et al., 1994). Dolerites have REE abundances 10 to 20 times chondritic values, whereas the basaltic rocks have approximately between 15 and 35 times chondritic values. One sample of volcanoclastic

**Table 1. Major- and trace-element analyses of Killara Formation rocks and mafic dykes in the Goodin Inlier**

Sample no.	104311 <sup>(a)</sup>	104312 <sup>(b)</sup>	104313 <sup>(b)</sup>	112798 <sup>(a)</sup>	112800 <sup>(a)</sup>	120392 <sup>(b)</sup>	120394 <sup>(b)</sup>	120396 <sup>(c)</sup>	136738 <sup>(c)</sup>	130918 <sup>(d)</sup>	130921 <sup>(e)</sup>
Easting	698823	699823	699655	717478	706299	707300	707300	707300	712614	722060	722967
Northing	7088627	7089076	7088614	7097500	7110396	7090900	7090900	7090900	7091692	7114962	7113100
<b>Percentage</b>											
SiO <sub>2</sub>	51.40	54.00	53.30	52.00	51.80	53.50	52.50	59.80	51.82	50.76	49.98
TiO <sub>2</sub>	0.68	0.93	0.98	0.80	0.80	0.84	1.17	0.66	0.82	1.04	1.19
Al <sub>2</sub> O <sub>3</sub>	14.20	12.50	13.40	13.50	13.70	14.60	13.80	15.20	13.41	13.94	14.42
Fe <sub>2</sub> O <sub>3</sub>	2.03	1.39	1.83	1.86	2.37	1.04	1.54	1.64	1.44	2.38	1.41
FeO	8.05	8.88	8.70	9.50	8.89	9.50	11.30	6.32	9.27	8.48	9.98
MnO	0.18	0.20	0.17	0.20	0.20	0.19	0.18	0.18	0.20	0.19	0.21
MgO	7.31	8.15	5.91	7.15	7.12	4.94	4.17	2.36	6.78	7.22	6.59
CaO	9.59	6.87	8.35	11.20	11.40	5.89	7.28	3.09	11.24	11.57	11.47
Na <sub>2</sub> O	3.31	4.73	4.74	1.67	1.63	4.40	2.45	1.39	1.45	1.67	2.51
K <sub>2</sub> O	1.14	0.14	0.48	0.07	0.08	0.49	1.64	4.39	0.59	0.25	0.20
P <sub>2</sub> O <sub>5</sub>	0.06	0.08	0.08	0.06	0.06	0.08	0.11	0.04	0.07	0.08	0.10
H <sub>2</sub> O <sup>+</sup>	3.07	3.43	3.08	2.57	2.85	2.81	2.34	3.32	—	1.38	1.47
H <sub>2</sub> O <sup>-</sup>	—	—	—	—	—	—	—	—	—	0.13	0.08
CO <sub>2</sub>	—	—	—	—	—	—	—	—	—	0.06	0.05
<b>Total</b>	<b>101.02</b>	<b>101.30</b>	<b>101.02</b>	<b>100.58</b>	<b>100.90</b>	<b>98.28</b>	<b>98.48</b>	<b>98.39</b>	<b>97.09</b>	<b>99.37</b>	<b>99.82</b>
<b>CIPW Norms</b>											
Q	—	—	—	6.32	6.70	1.33	5.18	20.38	6.14	4.99	—
C	—	—	—	—	—	—	—	2.53	—	—	—
or	6.76	0.83	2.84	0.41	0.47	2.90	9.52	25.99	3.49	1.48	1.18
ab	28.01	40.02	40.10	14.13	13.79	37.23	20.73	11.76	12.27	14.13	21.26
an	20.53	12.47	13.89	29.14	29.84	18.66	21.85	15.49	28.36	29.83	27.50
di	21.93	17.28	22.45	21.46	21.64	8.45	11.67	—	23.38	22.27	23.84
hy	7.25	16.49	6.31	22.21	20.53	23.65	22.40	15.38	20.73	19.35	18.61
ol	9.17	6.83	7.72	—	—	—	—	—	—	—	1.20
mg	2.94	2.02	2.65	2.70	3.44	1.51	2.23	2.38	2.09	3.45	2.04
il	1.29	1.77	1.86	1.52	1.52	1.60	2.22	1.25	1.56	1.98	2.26
ap	0.14	0.19	0.19	0.14	0.14	0.19	0.26	0.10	0.17	0.19	0.24
<b>Total</b>	<b>98.03</b>	<b>97.90</b>	<b>98.01</b>	<b>98.05</b>	<b>98.08</b>	<b>95.51</b>	<b>96.27</b>	<b>95.25</b>	<b>97.18</b>	<b>97.65</b>	<b>98.10</b>
<b>Parts per million</b>											
Sc	—	—	—	—	—	—	—	—	—	52	52
V	217	318	335	280	284	253	291	90	232	275	275
Cr	78	76	70	98	106	133	51	130	79	237	75
Mn	—	—	—	—	—	—	—	—	1 480	1 450	1 550
Co	—	—	—	—	—	41	45	24	61	55	62
Ni	87	58	61	94	69	87	50	85	67	92	71
Cu	146	117	110	148	140	131	121	19	160	50	49
Zn	70	89	80	99	83	95	108	118	85	96	96
Ga	14	12	14	14	15	0.5	2.2	2.1	15	15.0	15.0
As	4	4	4	4	4	0.8	0.5	0.5	0.5	1.0	1.0
Rb	47	4	17	2	2	15	58	119	20	12.5	1.5
Sr	292	61	284	125	123	58	140	112	158	167	212
Y	17	17	20	18	17	17	26	20	16	21	19
Zr	71	86	91	65	65	80	108	117	59	80	88
Nb	7.0	127.0	5.3	3.3	0.9	1.6	2.8	8.0	4.0	8.0	8.0
Sn	4.0	4.0	4.0	4.0	4.0	0.9	1.5	1.0	4.0	4.0	4.0
Ba	303	96	396	41	85	239	911	1 404	574	420	100
La	—	—	—	—	—	—	—	—	—	12	7
Ce	—	—	—	—	—	—	—	—	—	20	22
Pb	5	5	4	4	4	13	4	19	4	7	2
Th	3	5	6	2	3	4	3	14.8	2	1.5	1.5
U	2.0	1.5	2.0	0.4	0.3	1.0	1.3	2.4	0.05	0.05	0.5

Table 1. (continued)

Sample no.	130930 <sup>(a)</sup>	130939 <sup>(a)</sup>	130945 <sup>(a)</sup>	130956 <sup>(a)</sup>	130957 <sup>(a)</sup>	130977 <sup>(a)</sup>	130979 <sup>(a)</sup>	130985 <sup>(a)</sup>	130989 <sup>(a)</sup>	130992 <sup>(a)</sup>
Easting	706748	705479	709687	720460	722675	711181	709229	717056	720586	723215
Northing	7112220	7109882	7097757	7100465	7099070	7093797	7094150	7096393	7097340	7097594
<b>Percentage</b>										
SiO <sub>2</sub>	50.73	50.99	50.76	49.95	51.46	51.36	51.85	49.89	51.30	51.20
TiO <sub>2</sub>	0.56	0.61	0.68	0.77	0.71	0.82	0.75	0.70	0.68	0.65
Al <sub>2</sub> O <sub>3</sub>	13.91	14.34	14.28	14.50	13.34	13.25	13.48	13.74	13.66	13.84
Fe <sub>2</sub> O <sub>3</sub>	1.91	1.46	1.60	1.49	1.52	1.35	2.10	1.53	1.67	1.31
FeO	6.45	7.07	8.13	8.39	9.06	9.70	9.18	8.39	9.33	9.23
MnO	0.17	0.17	0.18	0.17	0.20	0.21	0.25	0.18	0.20	0.20
MgO	8.91	8.57	7.83	8.00	7.69	7.45	7.53	8.74	7.15	7.30
CaO	13.14	12.26	12.07	11.58	11.48	11.35	7.83	12.22	11.00	11.31
Na <sub>2</sub> O	1.12	1.51	1.68	1.92	1.67	1.46	3.78	1.29	1.68	1.66
K <sub>2</sub> O	0.20	0.32	0.20	0.16	0.26	0.34	0.18	0.46	0.35	0.33
P <sub>2</sub> O <sub>5</sub>	0.04	0.05	0.05	0.07	0.05	0.07	0.05	0.05	0.05	0.05
H <sub>2</sub> O <sup>+</sup>	2.54	2.39	2.07	2.52	2.48	2.32	2.92	2.50	2.43	2.43
H <sub>2</sub> O <sup>-</sup>	0.03	0.03	0.08	0.11	0.10	0.09	0.25	0.10	0.07	0.13
CO <sub>2</sub>	0.05	0.04	0.06	0.05	0.06	0.15	0.08	0.09	0.08	0.12
<b>Total</b>	<b>100.00</b>	<b>100.03</b>	<b>99.86</b>	<b>99.86</b>	<b>100.29</b>	<b>100.10</b>	<b>100.39</b>	<b>100.11</b>	<b>99.85</b>	<b>99.95</b>
<b>CIPW Norms</b>										
Q	4.75	3.29	3.17	1.30	4.31	5.02	–	2.08	4.74	4.08
C	–	–	–	–	–	–	–	–	–	–
or	1.18	1.90	1.18	0.95	1.54	2.01	1.07	2.72	2.07	1.95
ab	9.48	12.78	14.21	16.24	14.13	12.35	31.98	10.91	14.21	14.05
an	32.35	31.41	30.84	30.49	28.14	28.61	19.30	30.35	28.72	29.35
di	26.34	23.63	23.50	21.74	23.43	22.50	15.85	23.93	21.15	21.82
hy	19.14	20.97	20.86	22.54	22.26	23.23	21.25	23.42	22.42	22.63
ol	–	–	–	–	–	–	2.99	–	–	–
mg	2.77	2.12	2.32	2.16	2.20	1.96	3.04	2.22	2.42	1.90
il	1.06	1.16	1.29	1.46	1.35	1.56	1.42	1.33	1.29	1.23
ap	0.09	0.12	0.12	0.17	0.12	0.17	0.12	0.12	0.12	0.12
<b>Total</b>	<b>97.17</b>	<b>97.37</b>	<b>97.50</b>	<b>97.05</b>	<b>97.48</b>	<b>97.41</b>	<b>96.99</b>	<b>97.28</b>	<b>97.15</b>	<b>97.12</b>
<b>Parts per million</b>										
Sc	54	52	49	46	56	51	60	49	53	53
V	203	211	221	206	238	241	267	215	239	232
Cr	391	364	159	255	119	67	123	247	89	99
Mn	1 350	1 310	1 390	1 300	1 520	1 580	1 850	1 370	1 540	1 520
Co	60	57	61	61	65	68	65	67	64	64
Ni	147	134	96	132	85	78	74	130	78	78
Cu	137	122	95	69	142	113	66	86	153	133
Zn	64	69	78	79	83	89	92	79	87	83
Ga	12.5	13.0	13.5	15.5	14.0	14.0	12.5	13.0	13.5	13.5
Rb	6.0	11.0	5.5	2.5	12.5	12.0	4.5	21.0	13.5	10.5
Sr	119	110	126	181	134	109	120	124	135	126
Y	12	13	13	16	15	15	17	14	15	14
Zr	37	42	45	66	48	53	47	44	42	42
Nb	2	2	3	4	3	4	2	3	3	3
Sn	2	2	2	4	4	4	4	4	2	4
Ba	68	66	66	122	80	118	146	114	385	124
La	4	4	5	8	5	6	4	4	4	3
Ce	8	10	10	18	12	12	10	8	10	10
Pb	2	1	2	3	2	1	2	1	1	2
Th	1.0	1.0	0.05	1.5	1.0	1.5	1.0	1.0	0.5	2.0
U	0.05	0.05	0.05	0.05	0.05	0.5	0.05	0.05	0.05	0.05

## NOTES:

- (a) dolerite  
 (b) tholeiitic basalt  
 (c) volcaniclastic rock

- (d) mafic dyke (Goodin Inlier)  
 (e) tholeiitic basalt (Goodin Inlier)

Analyses were performed at the Chemistry Centre of the Department of Minerals and Energy, by XRF for major elements, following incorporation of sample into a borate glass disk, or a pressed powder. Co, Cr, Cu, Ni, V, and Zn were determined by ICP-AES following a mixed acid solution; all other analyte concentrations were quantified using ICP-MS after a mixed acid solution

SOURCE: Pirajno et al. (1998b)

**Table 2. Rare earth element analyses of dolerite and tholeiitic basalt of the Killara Formation**

Sample <sup>(a)</sup>	104312 <sup>(b)</sup>	112798 <sup>(c)</sup>	112800 <sup>(c)</sup>	120392 <sup>(b)</sup>	120394 <sup>(b)</sup>	136735 <sup>(c)</sup>	120396 <sup>(d)</sup>	136738 <sup>(d)</sup>	130918 <sup>(c)</sup>	130921 <sup>(b)</sup>	130930 <sup>(c)</sup>	130939 <sup>(c)</sup>	130945 <sup>(c)</sup>	130956 <sup>(c)</sup>	130957 <sup>(c)</sup>	130977 <sup>(c)</sup>	130979 <sup>(c)</sup>	130989 <sup>(c)</sup>	130992 <sup>(c)</sup>
Easting	699823	717478	706299	707300	707300	710445	707300	712614	722060	722967	706748	705479	709687	720460	722675	711181	709229	720586	723215
Northing	7089076	7097500	7110396	7090900	7090900	7090729	7090900	7091692	7114962	7113100	7112220	7109882	7097757	7100465	7099070	7093797	7094150	7097340	7097594
Parts per million																			
La	13.00	6.80	6.60	5.26	10.85	–	28.76	–	13.48	7.52	5.51	5.28	5.83	11.52	6.25	7.63	5.59	5.98	5.54
Ce	29.70	15.50	13.90	13.94	26.63	–	58.91	–	23.62	26.67	12.85	14.02	13.65	24.43	14.59	17.83	13.77	13.78	12.74
Pr	3.60	2.10	1.20	2.20	3.57	2.16	7.30	4.17	3.23	2.42	1.68	1.58	1.80	2.92	1.88	2.25	1.82	1.75	1.65
Nd	13.80	8.40	8.10	8.75	14.28	9.22	23.66	15.34	12.83	9.71	6.97	6.70	7.74	11.27	7.64	9.34	7.98	7.67	6.93
Sm	3.10	2.00	1.70	2.46	3.88	0.97	1.72	1.45	3.12	2.68	1.81	1.84	2.10	2.75	2.05	2.44	2.27	2.00	1.93
Eu	1.10	0.80	1.30	1.15	2.01	1.72	4.26	3.00	1.13	0.86	0.66	0.64	0.78	0.98	0.71	0.87	0.85	0.93	0.73
Gd	3.70	2.80	3.00	3.22	4.03	2.59	4.26	3.00	3.23	2.97	2.06	2.06	2.33	2.90	2.31	2.65	2.60	2.30	2.15
Tb	0.60	0.50	0.40	0.60	0.75	0.45	0.60	0.40	0.51	0.51	0.37	0.36	0.42	0.45	0.41	0.45	0.51	0.43	0.38
Dy	3.60	2.90	2.30	3.49	4.12	2.70	3.11	2.25	2.95	3.03	2.25	2.19	2.55	2.59	2.49	2.79	3.01	2.63	2.42
Ho	0.70	0.60	0.50	0.81	1.09	0.56	0.65	0.41	0.61	0.63	0.48	0.46	0.54	0.53	0.53	0.59	0.64	0.56	0.52
Er	2.20	1.90	1.30	2.22	2.92	1.72	1.86	1.29	1.81	1.88	1.45	1.43	1.65	1.60	1.60	1.78	1.99	1.75	1.56
Tm	0.30	0.30	0.20	0.42	0.14	0.25	0.33	0.18	0.26	0.26	0.21	0.21	0.25	0.22	0.23	0.25	0.28	0.25	0.23
Yb	1.90	1.70	1.00	2.31	2.62	1.78	1.62	1.26	1.81	1.82	1.56	1.47	1.74	1.54	1.69	1.88	2.01	1.85	1.70
Lu	0.30	0.30	0.20	0.50	0.59	0.26	0.44	0.18	0.28	0.25	0.23	0.22	0.27	0.23	0.25	0.28	0.27	0.28	0.26
Ce/Yb	15.63	9.12	13.90	6.03	10.16	–	36.36	–	13.05	14.65	8.24	9.54	7.84	15.86	8.63	9.48	6.85	7.45	7.49

**NOTES:** REE quantified using ICP-MS after a mixed-acid solution

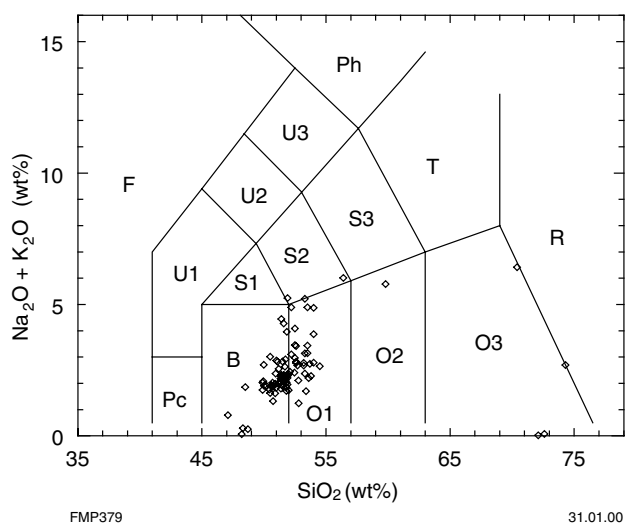
(a) GSWA sample number

(b) dolerite

(c) tholeiitic basalt

(d) volcanoclastic rock

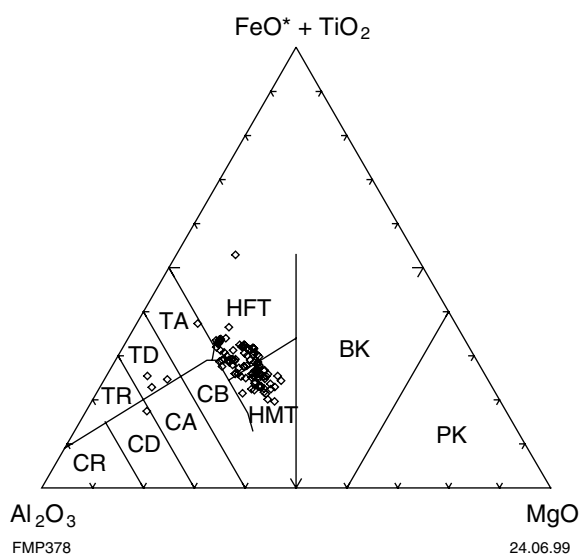
**SOURCE:** Pirajno et al. (1998b)



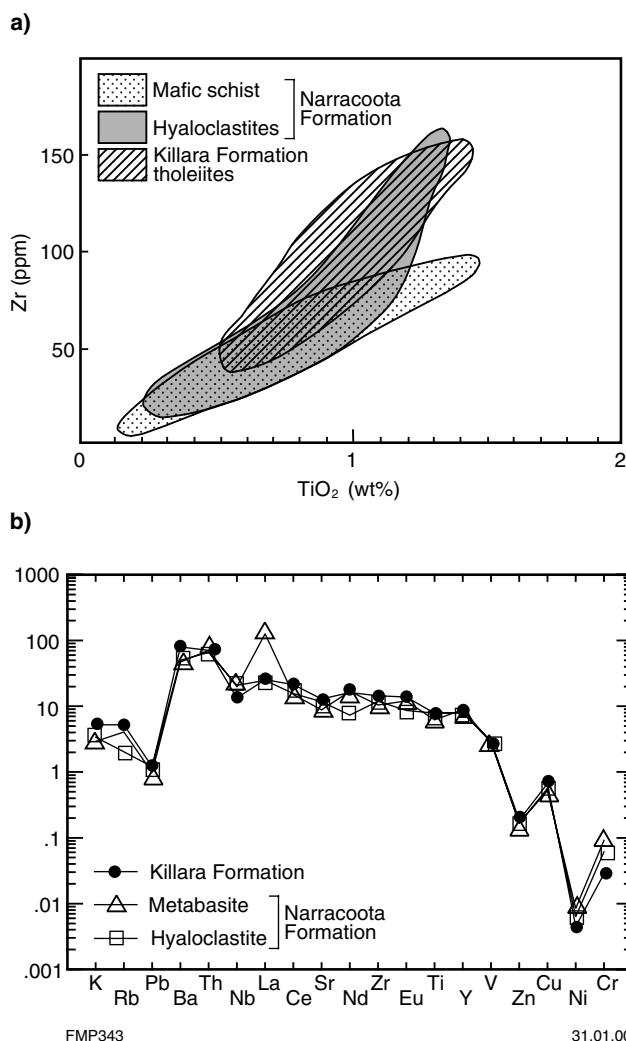
**Figure 17. Total alkali versus silica (TAS; Le Maitre, 1989) diagram, showing the range of rock types for the Killara Formation**

material is particularly LREE enriched (up to 80 times chondrite values) and slightly depleted in heavy REEs (HREE). A weak positive Eu anomaly indicates lack of plagioclase fractionation, perhaps due either to cumulate plagioclase or extraction of plagioclase. The similar patterns for basalt and dolerite confirm that they are cogenetic. The Killara Formation mafic rocks have high Ce/Yb ratios (>10; Table 2), which are typical of continental tholeiites (Green, 1992).

Based on the tectonic discriminant diagram of Figure 24, the mafic rocks of the Killara Formation have a dominantly continental geochemical signature. Again



**Figure 18. Cationic plot (after Jensen, 1976), showing predominant iron-rich tholeiite composition of the Killara Formation**



**Figure 19. Diagrams comparing the chemistry of the Narracoota (mafic schist and hyaloclastites) and Killara Formations: a) titanium oxide versus Zr; b) multi-element plot, normalized to chondrite. Normalization factors after Sun and McDonough (1989)**

this contrasts with the Narracoota Formation volcanic rocks, which have MORB- and oceanic plateau-like character (Pirajno and Davy, 1996; Pirajno et al., 2000).

A plot of chondrite-normalized REE abundances for rocks of the Bartle Member is shown in Figure 25. The Bartle Member has very low REE abundances, pronounced positive Eu anomalies ( $\text{Eu}/\text{Eu}^*_{\text{CN}}$  of 1.47 to 20.76), and a slight enrichment in LREE ( $\text{La}/\text{Yb}_{\text{CN}}$  of between 1.27 and 6.57; Pirajno et al., 1998c). The overall REE pattern matches that of the mafic rocks, except for the much less pronounced Eu anomaly. Similar REE patterns can be seen in the chert layers of banded iron-formation (BIF) from the Archaean Dharwar craton in India (Khan et al., 1996). In their study, Khan et al. (1996) concluded that the silica (and the iron) of the BIF was derived from hydrothermal solutions. The pronounced positive Eu anomaly is attributed to acidic, high-temperature hydrothermal fluids.

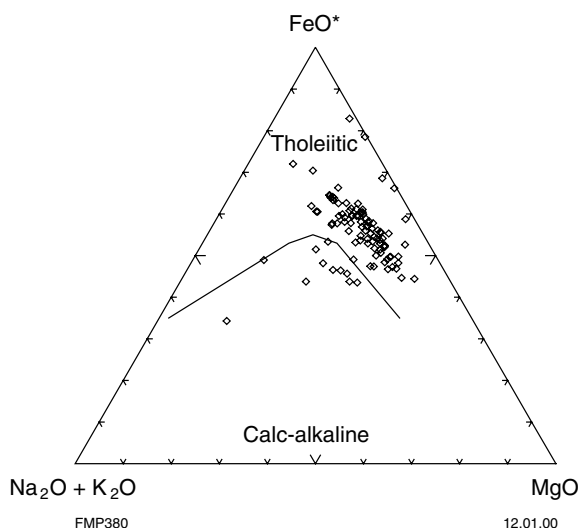


Figure 20. Triangular total iron – total alkali – magnesium oxide diagram, showing the tholeiitic trend of the Killara Formation

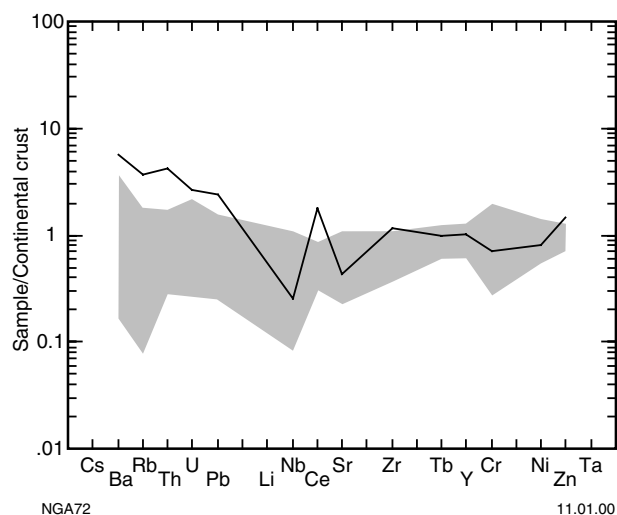


Figure 22. Multi-element diagram of Killara Formation rocks (shaded) and volcaniclastic rock (line), normalized to continental crust. Normalization factors after Taylor and McLennan (1985)

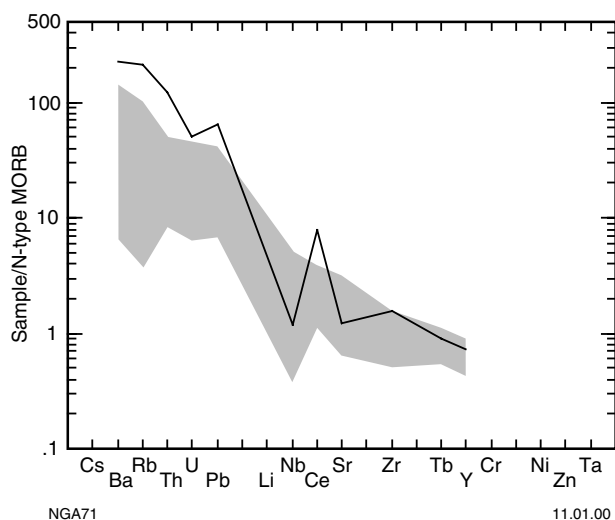


Figure 21. Multi-element diagram of Killara Formation rocks (shaded) and volcaniclastic rock (line), normalized to N-type MORB. Normalization factors after Sun and McDonough (1989)

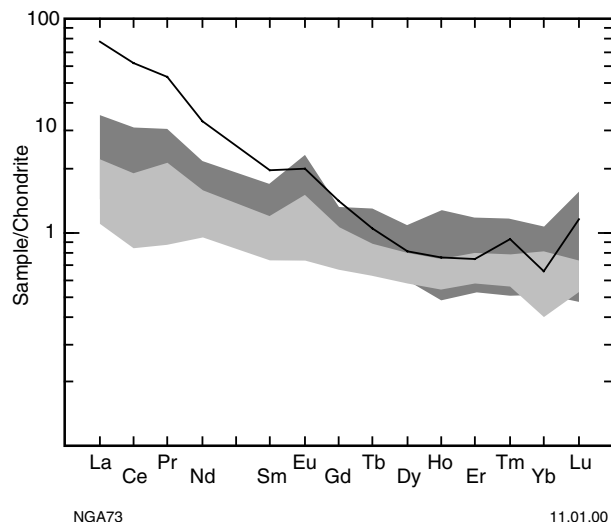


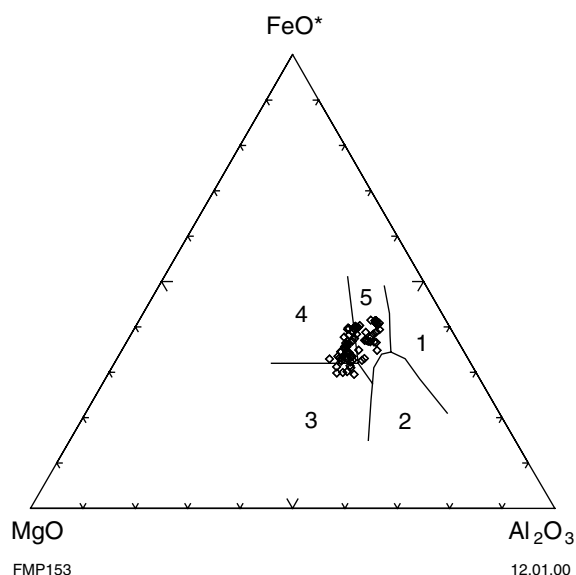
Figure 23. Chondrite-normalized rare earth element plot for Killara Formation dolerite (dark grey), tholeiitic basalt (light grey) and volcaniclastic rock (line). Normalization factors after Sun and McDonough (1989)

Trace-element analyses of Bartle Member rocks are presented in Table 3. Anomalous abundances of Au and Ba are recorded in these rocks.

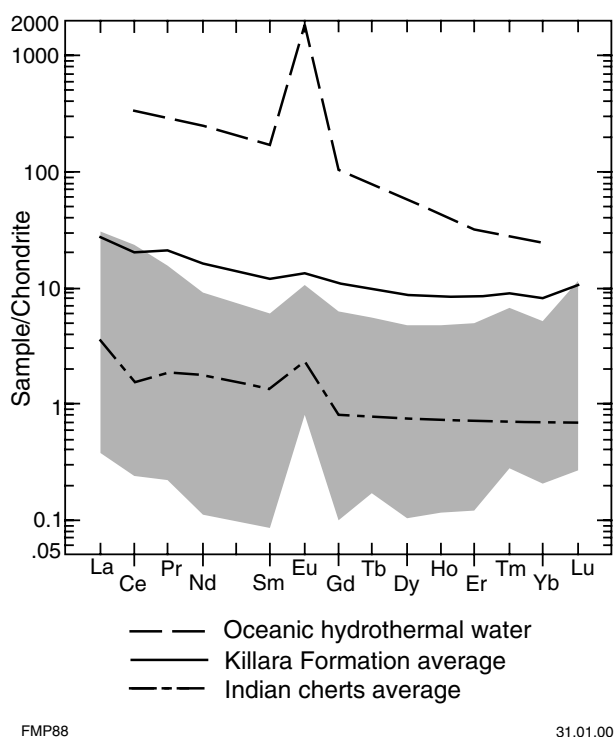
## Maraloou Formation

The Maraloou Formation (Bunting et al., 1977, Occhipinti et al., 1997) is a sequence of argillaceous sedimentary

rocks, black shale, marl, dolostone, and minor chert that forms the uppermost unit of the Yerrida Group (Occhipinti et al., 1997). The formation is named after Maraloou Well on MOUNT BARTLE. Elias et al. (1982) defined a type locality at Mount Russell, but there is no type section. The formation is extensively developed in the southern part of the Yerrida Basin, in a roughly triangular area from Diamond Well in the north to Willie Well in the east and Referendum Bore in the west. Outcrops are also present



**Figure 24.** Discriminant triangular plot (after Pearce et al., 1977), showing the tectonic environment(s) of the Killara Formation. Tectonic fields are as follows: 1) spreading centre; 2) orogenic; 3) ocean ridge; 4) ocean island; 5) continental



**Figure 25.** Chondrite-normalized rare earth element abundances in Bartle Member cherts (shaded) and oceanic hydrothermal water, and average of chondrite-normalized rare earth element abundances in Killara Formation mafic rocks and chert layers of Indian banded iron-formations (after Khan et al., 1996). Normalization factors after Taylor and McLennan (1985); oceanic water data after McLennan (1989)

**Table 3.** Whole-rock trace-element analyses of Bartle Member cherts

Sample no.	127522	127524	127526	127528	127545
Easting	779565	782289	782839	782839	782225
Northing	7097787	7101667	7095785	7095785	7103575
Parts per million					
Ag	0.1	0.8	0.1	0.1	0.5
As	0.5	3.4	2.8	2.3	0.5
Au (ppb)	37	48	56	66	35
Ba	105	46	392	4 055	97
Bi	0.8	1.3	1	0.7	1.3
Cr	36	51	29.3	32	49
Cu	15	11	10	14	22
Ga	1.4	7.3	1.4	5.2	5.1
Mo	0.8	1.3	2.1	0.4	0.1
Nb	0.5	4.6	1	3.4	2.7
Ni	11	27.5	6.3	10	67
Pb	6	13.6	17	11	10
Rb	1.3	2.8	0.6	6.3	14.2
Sc	23	17	28	15	21
Sr	9	9.5	49.4	56	11
Th	0.6	5	0.7	2.5	4.2
U	0.5	1.1	0.4	0.7	1
V	21	33	6.4	43	40
W	0.5	3.3	0.5	0.5	2
Y	0.5	4.4	0.5	2.9	16.5
Zn	1.7	50	9.5	5	34
Zr	18.6	36	12	27	61

**NOTES:** Analyses performed at the Chemistry Centre, Department of Minerals and Energy, by ICP-AES and ICP-MS following a mixed-acid dissolution

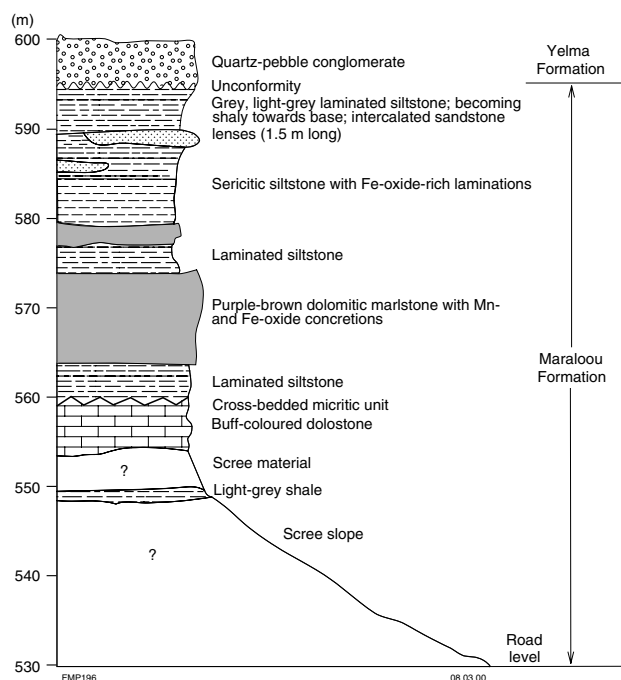
**SOURCE:** Pirajno and Grey (1997)

east of the Goodin Inlier from Cork Tree Bore to Quartermaine Well (on THADUNA) with smaller isolated outcrops in other areas.

The Maraloou Formation interfingers with the Killara Formation (Dawes and Pirajno, 1998), but unconformable contacts with the Doolgunna Formation have been observed on THADUNA (Pirajno and Adamides, 1998). The formation has unconformable relationships with the Juderina Formation. On THADUNA the unconformable contact between the Doolgunna and Maraloou Formations is defined by a synclinal sequence of silcretized chert breccia, with laminated Maraloou Formation siltstones exposed in the central parts of the syncline. Isolated outcrops, tentatively assigned to the Maraloou Formation, have been identified on GLENGARRY (Pirajno et al., 1998a), resting unconformably on rocks of the Juderina Formation. On MOUNT BARTLE the Maraloou Formation is inferred to onlap the Johnson Cairn Formation; however, contact relationships are not exposed (Dawes and Pirajno, 1998). The basal contact of the Maraloou Formation with the underlying Killara Formation is gradational and characterized by intercalated black shale, and mafic lavas and sills (Pirajno et al., 1998b).

The Maraloou Formation consists of sulfidic shale, finely laminated siltstone, argillaceous dolomitic limestone, and interbedded siltstone with thin beds of limestone and dolomite. The upper part of the formation is exposed in a 60 m section at Mount Russell (Fig. 26). The section consists of dolostone and argillite units that





**Figure 26. Measured stratigraphic section at Mount Russell (width of column reflects relative resistance to weathering)**

display decametre-scale rhythmic banding and metre-scale wavy banding. The dolostone is mostly massive to flaggy, pink to purple-brown, and commonly flecked with oxides of manganese and iron. The marlstone contains up to 80% dolomite; the balance is silt-sized quartz grains and clay minerals.

The lower parts of the formation consist of carbonaceous facies, with local bands of marlstone and carbonate nodules up to 50 cm in diameter. Drillcore and cuttings show sulfides (predominantly pyrite) that are locally abundant as cubes, framboidal aggregates, and nodules; and bands of carbonaceous and calcareous argillite with carbonate concretions, a few with sulfide cores. These features are interpreted as indicative of deposition under anoxic conditions.

On MOOLOOGUOL the Maraloou Formation (Pirajno et al., 1998b) consists of thin-bedded siltstone, carbonaceous shale, and quartz wacke intercalated with basalt and dolerite near the top. An east-northeasterly trending belt of fine-grained dolomitic rocks and calcareous siltstones overlies and flanks basalt and dolerite of the Killara Formation in central-western MOOLOOGUOL. The dolomitic units consist of packed aggregates of dolomite euhedra, which show zoning from a dark Fe-rich core surrounded by clear dolomite. The dolomitic rocks are variably silicified and chertified. They are intercalated with thin amygdaloidal basalts near the contact with the Killara Formation. Along strike from the dolomite are thinly bedded siltstone and black sulfidic shale. The latter consists of fine lenticles or laminae of silt-sized quartz grains, sericite, chlorite, kaolinite, iron oxides, and carbonaceous matter. Pyrite and chalcOPYRITE are the main sulfides, commonly replaced by secondary oxides and oxyhydroxides.

West of the Glengarry Range, the Maraloou Formation is predominantly well bedded and laminated, light-grey siltstone (Fig. 27). Individual beds range in thickness from 150 mm to 1 m and commonly display well-developed parallel stratification and colour banding in shades of greyish-brown and orange. These outcrops rest unconformably on chert of the Bubble Well Member. The siltstone has a moderately developed schistosity, with grains of subangular quartz and minor amounts of muscovite in a matrix of clays. These siltstones are underlain further east by carbonate units that are intercalated with minor fine-grained amygdaloidal basalt.

On GLENGARRY outcrops of uncertain stratigraphic position have been assigned to the Maraloou Formation. One of these, north of Daulby Well, consists of parallel-laminated and well-bedded siltstone, with individual beds from 100 to 150 mm thick and laminae defined by colour banding. Finely disseminated magnetite is locally present in the siltstones giving the rocks a high magnetic susceptibility (up to  $500 \times 10^{-5}$  SI units).

On MOUNT BARTLE the Maraloou Formation covers most of the southern half of the area, commonly underlying the flat alluvial outwash plain. Outcrops northwest of Mug Well, still on MOUNT BARTLE, contain lenticular bodies of micritic dolostone, which display upward fining and contain wavy and ripple cross-lamination. They also feature composite scour-and-fill structures, a few with intraformational conglomerate up to 20 cm thick, with clasts typically of granule size. These structures are interpreted as turbidite channel-fill bodies that accumulated on the slope of a carbonate-platform margin.

Another feature of the Maraloou Formation is the presence of turbidite beds of medium- to coarse-grained quartz wacke in stacks up to 2 m thick that have fluted and grooved basal surfaces. Fluted surfaces on outcrops north of Clarie Well on MOUNT BARTLE indicate northerly trending current flow, and those south of Maraloou Well have a northeasterly orientation. Isolated prod marks and flute morphology suggest a northerly current direction.



FMP 477

24.01.00

**Figure 27. Well-bedded siltstone of the Maraloou Formation, about 3 km southeast of Randal Bore**

This points to a marginal-slope to basinal depositional setting for the Maraloou Formation with a source area to the south.

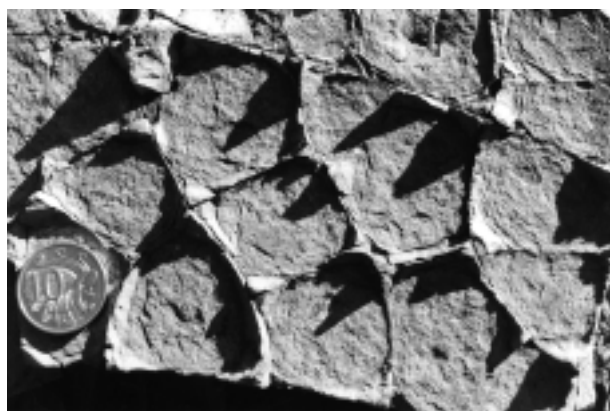
The siltstones of the Maraloou Formation on GLEN-GARRY are mainly parallel laminated on millimetre scale. Local mudcracks (Fig. 28) suggest shallow-water conditions with possible local emergence. The low-energy depositional environment, lithological associations (shale, marl, micritic carbonate), and the rhythmically laminated rocks of the Maraloou Formation suggest that they were deposited in a lacustrine setting.

## Earaheedy Group

The Earraheedy Group is present within the Yerrida Basin as scattered outliers southeast and northwest of the Goodin Inlier (Plate 1). These outliers have been correlated with the basal unit of the Earraheedy Group, the Yelma Formation. To the northeast the Yerrida Group is partially masked by the unconformably overlying Yelma Formation, which in this area represents the westernmost reaches of continuous cover by the Earraheedy Group.

## Yelma Formation

The Yelma Formation is a unit of clastic and dolomitic sedimentary rocks at the base of the Earraheedy Group. This unit is present near and around Lake Gregory, in the northeastern part of the Yerrida Basin (Plate 1), and consists mainly of quartz arenite, stromatolitic dolomite, and chert breccia. The base of the Yelma Formation includes quartz lithic sandstone and quartz conglomerate, which lie unconformably on quartz arenite of the Finlayson Member, and is exposed 1.5 km east of Freshwater Well, on the southern edge of Lake Gregory. The main constituents of the lithic sandstone near the base of the formation are quartzose and sericitized lithic grains, and subordinate polycrystalline quartz, chlorite, and turbid feldspar.



FMP 239

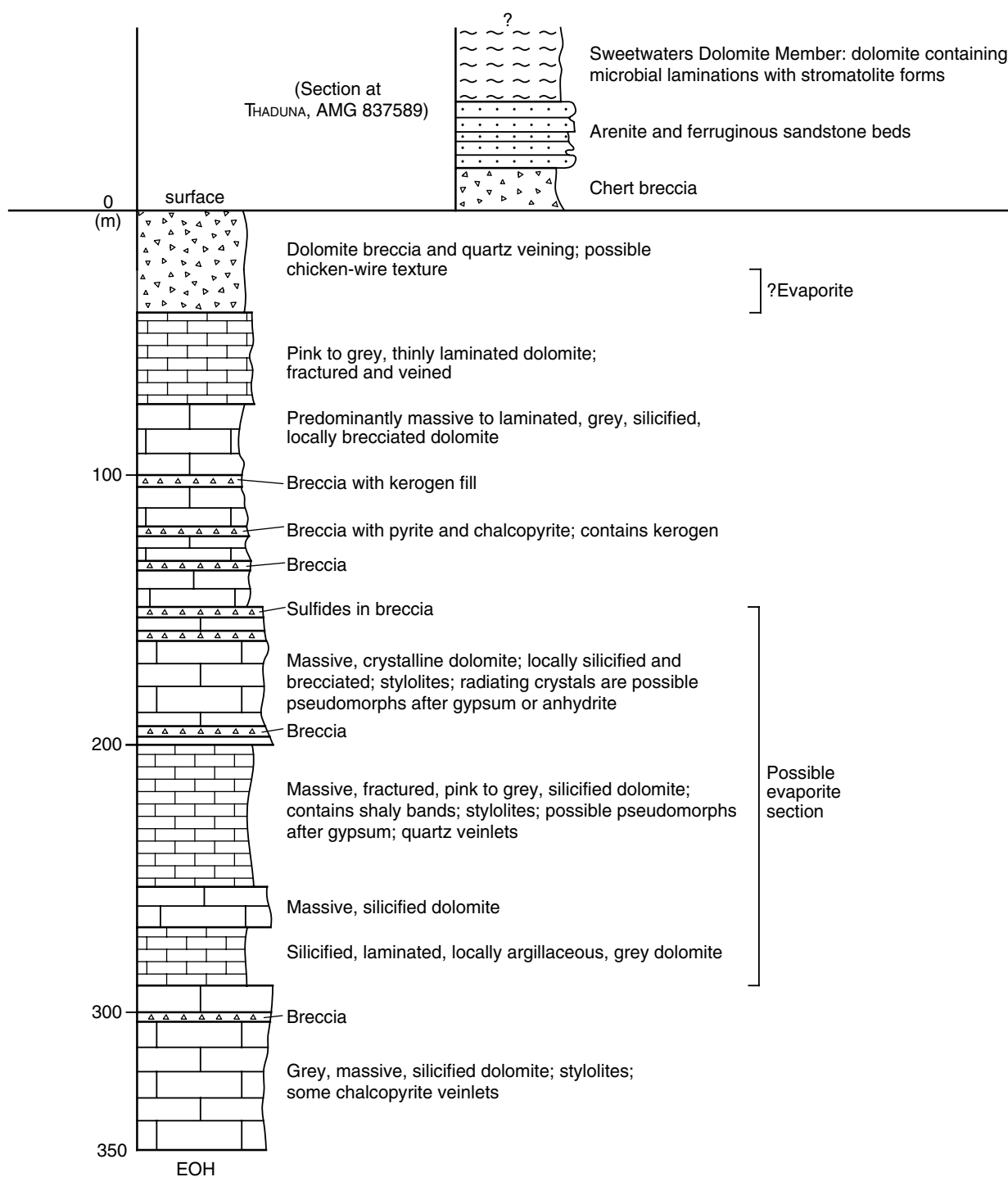
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**Figure 28. Mudcracks in thin-bedded siltstone of the Maraloou Formation. Coin is 23 mm in diameter**

Two boreholes drilled 3 km south of Little Well (CTW 001 and CTW 002; Meakins and Watsham, 1994), combined with field observations, provide a representative 400 m-thick stratigraphic section of the Yelma Formation. The lower part of this section, schematically represented in Figure 29, consists of grey to pink, massive, silicified dolomite beds. Argillaceous interbeds are locally present between 350 m and about 200 m below surface. This interval is overlain by a 120 m-thick unit of dolomite with solution breccia interbeds, containing some interstitial kerogen material and sulfides. This is in turn overlain by about 100 m of pink to grey thinly laminated dolomite, dolomite breccia, ferruginous sandstone, and arenite, followed by 20 m of dolomite with microbial laminae. The latter is a distinctive rock, which may be part of the Sweetwaters Well Member (new name for a proposed member of the Yelma Formation, to be formally defined; Pirajno et al., 1999), which is well exposed to the east on the NABBERU 1:250 000 sheet. Stromatolites in the Sweetwaters Well Member include *Asperia digitata*, *Pilbaria deverella*, and *Ephyalthes edingunensis* Grey 1994. They outcrop at a number of localities on the northwestern side of Lake Gregory (Fig. 30). Grey (1984, 1994a,b) suggested that these stromatolite forms are indicative of an upward-shallowing, lagoon to supratidal environment.

Outcrops on the northwestern side of Lake Gregory consist of commonly chertified dolomite breccia (Fig. 31), and cream-coloured and fine- to medium-grained, bedded to laminated dolostone with minor lenses of ferruginous sandstone and siltstone, associated with stromatolitic dolostone. Around Edingunna Spring, outcrops of these units include silcretized chert breccia, which is underlain by coarse breccia, associated with granulestone, and contains rounded pebbles. This material is underlain by pebble beds, about 2 m thick, comprising subrounded to rounded pebbles up to 5 cm of dominantly quartz and chert, and a coarse-grained, poorly sorted quartz (and ?feldspar) arenite, underlain by more pebble beds. Most dolomitic rocks consist of a packed aggregate of small (averaging 0.1 mm) dolomite rhombs, with interstitial iron oxides. The dolomite also locally contains disseminated quartz grains and submicroscopic stylolites. Siltstone interbeds contain quartz, kaolinite, illite, and sericite. In drillhole CTW 002, sulfide mineralization (mainly pyrite and chalcopryrite) is associated with specks of kerogen in dolomite breccia. Breccia clasts are rimmed by fine pyrite and kerogen, and open spaces are filled with euhedral quartz and chalcedony.

Outliers of the Yelma Formation in the southeastern part of the Yerrida Basin are present on MOUNT BARTLE and MEREWETHER. The rocks outcrop as a series of low rubbly mesas and ridges in the Spinifex Range. Here, the Yelma Formation is less than 60 m thick, and commonly only a few metres are preserved as a weathered veneer over the Yerrida Group. The overlying regolith forms irregular bouldery lags, laced with drusy quartz, chalcedony, and chert. The correlation of these rocks with the main outcrops of the Yelma Formation to the east, in the Earraheedy Basin, was made by Gee and Grey (1993) and Grey (1994a,b) on the basis of lithology and stromatolite morphology.



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Figure 29. Composite stratigraphy of the lower part of the Yelma Formation, derived from drillcore and outcrops near Lake Gregory (after Pirajno and Adamides, 1998; width of column reflects relative resistance to weathering)



FMP293

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**Figure 30. Stromatolite form *Ephyaltes edingunnensis* Grey 1994 in dolomitic rocks of the Yelma Formation, northwestern side of Lake Gregory**

These outliers are incompletely preserved and typically poorly exposed, and they appear to be unconformable on the Yerrida Group. The gently folded rocks of the underlying Maraloou Formation in the Spinifex Range, south of Yandil Homestead and southeast of Paroo Homestead, display a very low angle unconformity.

The rocks of these outliers include bedded quartz-pebble conglomerate and cross-bedded sandstone. This is overlain by mixed micritic and stromatolitic dolostone, intercalated with graded laminated and flat-bedded calcareous arenite and argillite, and micritic dolostone, and overlain by bands of chert and chert breccia. Gee and Grey (1993) pointed out that the base of the Yelma Formation is similar to the Finlayson Member, the basal unit of the Yerrida Group, with which it has been confused in the past. However, the basal arenite unit can usually be distinguished from the Finlayson Member by a coarser grain size, thicker bedding, weaker cementation, and abundance of trough cross-bedding. The dolostone and chert units can be readily distinguished where stromatolites are present, using stromatolite morphology (see below).

A coarse mosaic of dolostone breccia with a micritic dolostone and hematite cement is present along the southern and western flanks of the Spinifex Range in the southeastern part of the Yerrida Basin. This breccia could be a collapse breccia associated with dissolution of evaporite minerals or, less probably, debris associated with carbonate reefs.

The overall depositional sequence indicates a broad transgressive event. This is an upward-fining sequence of siliciclastic rocks, commonly a medium- to coarse-grained quartz arenite throughout the Spinifex Range. A basal clast-supported conglomerate up to a few metres thick is locally preserved. This is best seen approximately 3 km southwest of Mug Well on Paroo Station. The conglomerate grades laterally and vertically into cross-stratified quartz arenite. The clasts in the conglomeratic bodies are predominantly irregular subangular varicoloured cherts up to 10 cm in diameter, minor subrounded vein quartz, and

quartz arenite clasts, all set in a matrix of fine- to coarse-grained quartz arenite. The quartz arenite is commonly pale buff and medium grained, with a variety of sedimentary structures that include trough cross-stratification and, locally, broad shallow low-angle trough cross-bedding. Other outcrops are on top of the mesas south of Yandil Homestead. The basal conglomerate appears to thin to the south and west, and in the western Spinifex Range is restricted to quartz arenite and quartz-pebble layers a few tens of centimetres thick.

A few exposures show bipolar and bimodal cross-lamination, suggestive of tidal deposition. Irregular stacked, decimetre-scale, upward-fining couplets of clast-supported conglomerate overlain gradationally by tongues of crudely cross stratified quartz arenite are present locally. These have little to no clay component, either as drapes or matrix and, together with field relationships, are indicative of high-energy deposition. The overlying quartz arenite commonly thickens at the expense of the conglomerate, the unit as a whole seldom exceeding 5 m. Trough cross-lamination is widespread, with a variety of current directions, predominantly to the north. A coastal beach barrier setting with tidal inlets is probable, based on all these features.

Stromatolitic dolomite forms units consisting of a few tens of metres of intercalated calcareous argillite, micritic dolostone, and microbial-laminated and stromatolite-bearing dolostone, with bands of chertified dolostone strata. Gee and Grey (1993) and Grey (1994a,b) showed that the stromatolite succession is characterized by diagnostic taxa, and specimens from new localities are not only consistent with distributions previously recorded, but also suggested that further refinement of the stratigraphic subdivision is feasible. The diagnostic taxa, *Yandilla meekatharrensensis* and *Yelma digitata*, are illustrated in Grey (1984). In addition, the grey dolostone contains the branching columnar, niched stromatolite *Pilbaria deverella* and the asperiform mini-stromatolite *Yelma digitata* in outcrops in the Spinifex Range between Cookies Bore and Corner Well. The resolution of lower and upper stromatolitic units as determined by Gee and



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**Figure 31. Chert breccia derived from dolomite of the Yelma Formation, near Lake Gregory**

Grey (1993, fig. 11) has not been confirmed, and *Ephyaltes* f. indet. outcrops have been located apparently only a few metres above the basal quartz arenite. Exposures are rare and deeply weathered. However, an intercalation of at least four stromatolitic cherty dolostone benches can be discerned in the hills southeast of Crystal Well on Paroo Station. Each bench is 1 to 2 m thick and separated by thinner hummocky units of stratified calcareous silty sandstone. These stromatolitic units show a vertical cyclicity from the stratified calcareous sandy siltstone upwards into undulose microbial mats that develop vertically into columnar forms. The stromatolitic units are commonly chertified and resist erosion, particularly between Crystal Well and Corner Well on Paroo Station.

Chert and chert–dolostone breccia and fractured laminated strata are intercalated with locally silicified stromatolitic dolostone units. Field observations show these units to be areally extensive and it is possible that the fractured and brecciated horizons are palaeo-aquifers, contained between relatively impermeable stromatolitic units. Pervasive silicification resulted in a gradual build-up of fluid pressure and consequent hydraulic fracturing when this pressure exceeded the lithostatic load. Alternatively, these breccias may be the result of dissolution of evaporitic and carbonate beds.

## Mount Leake Formation

Outliers of the Mount Leake Formation are present west of the Goodin Inlier. The Mount Leake Formation straddles the Goodin Fault, which marks the tectonic boundary between the Bryah and Yerrida Basins. This clearly demonstrates that the Mount Leake Formation was deposited well after the tectonic juxtaposition of the Bryah and Yerrida Groups. The Mount Leake Formation commonly trends easterly and dips shallowly to the north.

The Mount Leake Formation consists of a basal jasperoidal chert and green chert breccia, approximately 2 m thick. This is followed upward by a ferruginous sandstone layer and by layers of cross-bedded, locally glauconitic quartz arenite. The basal jasperoidal chert breccia may be a palaeoregolith material (perhaps a silcrete) developed on the unconformity surface of the Bryah Group (Pirajno and Occhipinti, 1998) prior to the deposition of the Mount Leake sedimentary rocks. On the basis of stromatolite taxa, the Mount Leake Formation was correlated with the Yelma Formation of the Earahedy Group (Adamides, 1998). This correlation is uncertain, but if correct then the Yelma Formation of the Earahedy Group was deposited well after the tectonic juxtaposition of the Bryah and Yerrida Groups.

## Mafic dykes

Normal- and reverse-polarized linear magnetic anomalies can be seen on total magnetic intensity images (from an aeromagnetic survey flown by Tesla Airborne Geoscience over the PEAK HILL 1:250 000 map sheet; Gee, 1987). These features are interpreted as mafic dykes on the basis

of outcrops associated with linear magnetic anomalies on MOOLOOGOO and MOUNT BARTLE (Pirajno et al., 2000; Dawes and Pirajno, 1998). These mafic dykes intruded the Maralooou Formation and are therefore younger. In this Report it is assumed that these dykes are of Proterozoic age, although no absolute age determinations are available.

There are four groups of dykes, each with different orientations. In the northern part of the Yerrida Basin, mafic dykes trend northeasterly and are subparallel to the Jenkin Fault along the contact of the Marymia Inlier (Plate 1). In the southern and eastern parts of the Yerrida Basin, dykes trend easterly and northeasterly and cut an older set trending west-northwesterly. These two sets are probably part of a larger swarm along the northern margin of the Yilgarn Craton. The fourth group of dykes is east-south-easterly trending and intruded the Goodin Inlier. Samples of this latter group suggest that they are cogenetic with the Killara Formation. Only a few dykes outcrop in the Yerrida Basin, cutting through the Maralooou Formation.

Dykes are locally visible on aerial photographs as linear, lightly vegetated areas. The dykes commonly form very shallow elongate lateritized furrow-shapes. The contacts are locally marked by small outcrops of dark ironstone. The Goodin Inlier dykes have a holocrystalline doleritic texture with interlocking andesine to labradorite ( $An_{50}$ ) plagioclase laths and abundant hornblende. Grain size varies from 0.8 to 1 mm. The plagioclase is fresh, locally zoned, and may enclose fine-grained amphibole needles. Locally, amphibole constitutes up to 70% of the rock and comprises strongly pleochroic (yellow-green to deep blue-green), probably sodic, hornblende. Quartz is present in variable amounts and commonly exhibits myrmekitic intergrowth with plagioclase. Euhedral opaque crystals, 0.04 mm in size, of the ilmenite–titanomagnetite group are completely replaced by finely granular titanite. One sample collected from a mafic dyke near Utahlarba Spring also contains minor amounts of brown biotite in addition to hornblende.

Modelling of the easterly and west-southwesterly trending magnetic anomalies indicates that they are tabular bodies, best interpreted as dykes. As mentioned above, a few dykes do outcrop, but the majority of the magnetically delineated dykes have depth estimates based on modelling of between 70 and 200 m below ground level, with a few between 300 and 500 m below ground level. Dips are steep to the north or south. A few dykes are vertical.

The same dykes, however, outcrop in the adjacent granite–greenstone terranes. It is assumed, therefore, that dykes stop at or close to the Archaean–Proterozoic unconformity (Plate 2). A possible explanation is based on the concept of neutral buoyancy level, whereby a silicate melt rises through the lithosphere and stalls at the base of the crust due to the rheological barrier posed by the lower density of crustal materials, thus creating a zone of neutral buoyancy (Best, 1982). The melt ponds at the lithosphere–crust boundary and dykes propagate from the ponded melt intruding the granite–greenstone rocks, but solidifying before they reach the unconformity surface and the overlying Proterozoic cover rocks. However, a few dykes cut through if they have sufficient overpressuriz-

ation, perhaps due to build-up of volatiles or through the arrival of fresh melts along the same channel.

In the southeastern part of the Yerrida Basin, the magnetic pattern of one of these east–west trending dykes indicates segmentation of the dyke subcrop. This interesting dyke structure may be an effect of the difference between stress fields at depth and near the surface. During emplacement the dyke may rotate into the near-surface stress field, resulting in the segmentation (Ernst et al., 1995, p. 4).

## Quartz veins

Quartz veins form prominent ridges in the northern part of MOUNT BARTLE. Two main directions are present: north to slightly west of north and east to east-southeast. The northerly trending veins are concentrated in several swarms in two areas: the Kimberley Range in the eastern part of the Yerrida Basin and on the eastern border of the map sheet. In the latter area the veins are part of a small swarm that continues eastward. The easterly trending veins are in the west, more specifically, east and west of the Large Gum Creek.

Quartz veins commonly reach up to a metre across, although one compound northerly trending vein is up to 4 m across. Outcrops commonly consist of several subparallel veins and veinlets. Many veins and veinlets have sinuous contacts, and thicknesses vary along strike.

Many of the quartz veins are ferruginized. Crushing of quartz and shearing of wall rock indicate some post-emplacement dislocations. Small sulfide flecks are associated with quartz in some veinlets.

There is a clear relationship between the main trends of the quartz veins and the major structural lineaments. The north to north-northwest trends are parallel to the dominant trend of the Archaean basement, suggesting reactivation of the Archaean structures during the Proterozoic.

## Metamorphism

Rocks of the Yerrida Group are commonly unmetamorphosed to weakly metamorphosed. Groundmass material of clastic sedimentary rocks exhibits partial alteration of kaolinite to illite or sericite. These mineral assemblages suggest temperatures of about 300°C and pressures equal to, or less than, 3 kbar (Bucher and Frey, 1994). The mafic rocks of the Killara Formation contain minor amounts of quartz, actinolite, chlorite, prehnite, calcite, epidote, and possibly stilbite as metamorphic minerals. This low-grade metamorphic assemblage straddles the subgreenschist to greenschist-facies boundary and is consistent with temperatures of between 100 and 250°C and pressures of approximately 2 to 6 kbar (Bucher and Frey, 1994).

Rocks of the Juderina Formation adjacent to the dolerite sills have a contact metamorphic assemblage of

epidote, clinozoisite, prehnite, chlorite, carbonate, titanite, and albite. The chlorite is faintly pleochroic with first-order grey birefringence and is closely associated with carbonate. Pyrite is present in the form of euhedral crystals within the carbonate and is clearly related to the alteration assemblage. Fresh albite is interstitial to quartz. Carbonate rocks, proximal to dolerite, are locally recrystallized to a coarser grained aggregate and locally contain a quartz–kaolinite assemblage infilling voids.

Lower greenschist-facies metamorphism affects the Archaean granitoid rocks of the Goodin Inlier and the sedimentary rocks of the Juderina Formation around its southern margin. Albite, sericite, epidote, and chlorite are the most common mineral phases.

## Structure and deformation

The strata of the Yerrida Group are commonly flat lying to moderately northerly dipping in the southern part of the Yerrida Basin. The Maraloou Formation is commonly flat lying or with shallow southerly dips. Poor and discontinuous outcrop prevents definition of detailed fold geometry, but scattered dip and strike readings suggest that the Yerrida Group rocks may be weakly folded by low-amplitude, north-northwesterly to northeasterly trending, open folds. Rocks of the Juderina Formation on the eastern margin of the Yerrida Basin are flat lying to westerly dipping. This tilting of the sedimentary strata was probably the result of the rifting that resulted in the outpouring of the mafic lavas of the Killara Formation. This is indicated by the intrusion of sills within the siliciclastic layers of the Juderina Formation and the onlap of argillaceous sediments of the Maraloou Formation in the area.

The Earahedy Group outliers in the southeast and outcrops around Lake Gregory in the northeast are undeformed and unmetamorphosed. This indicates that the age of the deformation in the area is older than the basal parts of the Earahedy Group.

The most prominent structures in the region are the northeasterly trending Goodin and Jenkin Faults. The Goodin Fault is a moderately northwesterly dipping thrust contact between the Yerrida and Bryah Groups, and the near-vertical to steeply northwesterly dipping Jenkin Fault separates the Yerrida Group from the Marymia Inlier (Plate 2). The Yerrida Group is deformed along the Goodin Fault, with tight to isoclinal folding affecting rocks of the Doolgunna Formation, and fold axes oriented subparallel to the fault. Deformation decreases southeastward to where strata are gently dipping.

On MARYMIA, Bagas (1998) recognized three Palaeoproterozoic and Mesoproterozoic deformation events ( $D_3$ ,  $D_4$ , and  $D_5$ ). The  $D_3$  structures relate to a northwest–southeast extension, which may have controlled the deposition of the Mooloogool Subgroup in a rift-basin setting (Bagas, 1998). The  $D_4$  event is characterized by open to tight, northeasterly trending folds, which are the result of southeasterly directed thrusting during the Capricorn Orogeny, and which also resulted in the thrusting of the Marymia granite over the Yerrida Group

along the Jenkin Fault (Bagas, 1998). The D<sub>5</sub> event is a north–south compression, which produced northeasterly and southeasterly trending faults, some of which host dolerite dykes of possible Mesoproterozoic age (Plate 1). During D<sub>5</sub>, the Jenkin Fault was reactivated as a sinistral strike-slip fault.

Away from the Goodin and Jenkin Faults, deformation decreases and the strata of the Yerrida Group only display open folds, with northeasterly trending fold axes, particularly on the eastern side of the Goodin Inlier (Plate 1). One of these fold structures is a northeasterly plunging anticline in the Gum Creek area, informally named the Diamond Well anticline (Dawes and Pirajno, 1998).

The granitoid rocks of the Goodin Inlier locally have a northeasterly trending gneissic foliation, with mylonitic zones in the southern margin of the inlier. The dominant structural fabric of the rocks around the Goodin Inlier is attributed to a D<sub>1</sub> event (Pirajno et al., 1998b), which developed during the Capricorn Orogeny, and corresponds to Bagas' (1998) D<sub>4</sub> event. During this time the Goodin Inlier acted as a stable buttress and the rocks around it were variably deformed. Evidence of internal deformation of the Goodin Inlier are west-northwesterly trending D<sub>1</sub> fractures and faults, along which mafic dykes were emplaced. The southwestern contact of the Goodin Inlier is defined by a series of high-angle shear zones, probably with an accompanying reverse movement, resulting in the tectonic slicing of the unconformable contact between the granite and the Juderina Formation. Thus, the contact between the Marymia Inlier and the basal units of the Juderina Formation is characterized by intense deformation associated with mylonitization and intrafolial folding. The west-northwesterly trending faults in the Goodin Inlier can be magnetically traced eastward, across the Kimberley Range, beyond which they merge with mafic dykes.

A system of easterly trending normal faults is inferred from the presence of dykes that trend in the same direction, in the southern part of the Yerrida Basin. These faults may represent growth faults associated with the inception of rifting.

## Mineralization

Mineral deposits and occurrences of the Yerrida Basin include copper in shear zones and base metals in sedimentary rock. The distribution of these mineral deposits and occurrences is shown in Plate 1.

### Base metals

The only known copper deposits include Lee (Ricci), the old Thaduna copper mines, North prospect (position unknown), Rooneys mine, and Green Dragon, all in the northern part of the Yerrida Basin. These constitute the Thaduna copper deposits, none of which are currently in production. The Thaduna copper deposits produced a total of 2823 t of copper metal and remaining inferred resources

average 3.4% Cu and contain about 17 000 t of copper metal (Pirajno and Preston, 1998). The deposits are epigenetic and related to a northeasterly trending fault within the Thaduna Formation. The mineralization is found within northwesterly trending, quartz-filled shear zones. Host rocks near Thaduna mine include two lithic sandstone units separated by siltstone. The Thaduna mine produced oxide ore (malachite, cuprite and chrysocolla), and was mined to a depth of about 50 m (Pirajno and Preston, 1998). The Thaduna copper lode follows the northeasterly trending Thaduna Fault, in which the mineralization is up to 23 m wide. The bulk of the lode consists of sheared and brecciated sedimentary rock, containing abundant hydrothermal graphite associated with quartz and carbonate minerals. Below the depth of mining, ore minerals are chalcopyrite and bornite with supergene chalcocite and rare covellite. The ore contains anomalous gold (up to 260 ppb). The old Lee (or Ricci) copper deposit, 3 km south-southwest of the Thaduna mine, is hosted by weathered lithic sandstone and shale. The principal mineralized shears strike at 350°. The mineralization is in the form of 1–3 m-wide zones of graphitic breccia cemented by limonite and quartz associated with secondary copper minerals.

A number of mineralized occurrences outcrop in the form of stratabound gossans and fault-associated gossanous quartz veins, 10 to 15 km northeast of Killara Homestead. Stratabound gossans, derived from the oxidation of sulfide mineralization, are present in the siltstone – black shale succession of the Maralooou Formation, and thinly bedded arenaceous units of the Juderina Formation. Black shale-hosted gossans form small, sparse outcrops, distributed along a strike length of approximately 6 km, 2.5 km south of Rockhole Bore. These gossans are situated parallel to, or along, the contact between the Maralooou and Killara Formations. They consist of hematite, goethite, and limonite forming well-defined boxworks after sulfides, in places cut by veins of goethite and limonite. Relict sulfides are locally recognizable and consist of pyrite and chalcopyrite. The black shale-hosted gossans have anomalous Ba, Pt, Pd, Cu, and Zn (Table 4).

Approximately 3 km east of North Bore, the same stratabound zone of sulfide mineralization was intersected by drillholes GD-1, GD-2, and GD-3, at depths of between 90 and 100 m (Guj and McIntosh, 1984). This is a zone of hydrothermal alteration and disseminated sulfides, hosted in a gabbroic sill, which intruded pyritic black shales of the Johnson Cairn Formation (Fig. 32). The zone is at the base of the sill, and parallel to the contact with underlying black shale units. Hydrothermal mineral phases in the gabbroic rock include epidote, biotite, hornblende, chlorite, sericite, and aggregates of microcrystalline montmorillonite clays. Granophyric intergrowths (quartz–feldspar) are associated with this alteration. Sulfides are pyrite, chalcopyrite, pyrrhotite, and lesser arsenopyrite. Assays of core from three drillholes revealed anomalous gold (20 to 33 ppb), zinc (1360 to 2230 ppm), and copper (650 ppm) in core lengths less than 3 m (Guj and McIntosh, 1984).

In northwestern MOOLOOGOO, gossans hosted in the thinly bedded arenaceous units of the Juderina Formation

Table 4. Trace-element analyses of gossans

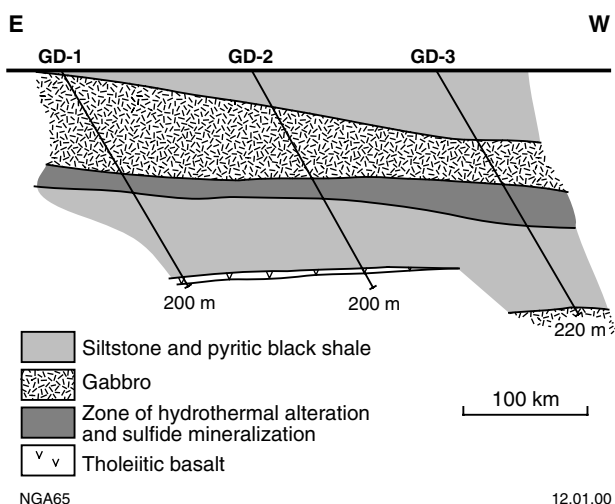
Sample no.	137743A <sup>(a)</sup>	119423 <sup>(a)</sup>	119424 <sup>(a)</sup>	119425 <sup>(a)</sup>	P173143 <sup>(b)</sup>	P173146 <sup>(b)</sup>	P173147 <sup>(b)</sup>	P173148 <sup>(b)</sup>	P173160 <sup>(b)</sup>	130916 <sup>(c)</sup>	130940 <sup>(d)</sup>	130943 <sup>(e)</sup>	130944 <sup>(f)</sup>	130948 <sup>(e)</sup>
Easting	715625	718400	714000	709500	709400	709400	709400	709400	709400	721251	712232	710208	710005	705488
Northing	7090692	7091500	7091300	7087300	7120000	7120000	7120000	7120000	7120000	7112427	7114223	7098337	7098087	7099400
Parts per billion														
Au	3	—	—	—	33	6	81	19	3	1	—	—	—	—
Pt	23	5	5	5	22	26	21	3	6	—	—	—	—	41
Pd	6	8	1	1	8	5	3	24	3	1	—	—	—	16
Parts per million														
Cr	43	26	66	32	16	37	5	60	109	6	6	22	54	97
Co	2	18	11	138	38	10	74	75	12	11	8	19	282	23
Cu	251	260	27	447	2 770	2 000	12 400	2 180	100	683	170	499	205	1 778
Ni	44	57	91	463	164	20	132	89	81	23	33	39	275	178
Sc	31.0	24.0	5.2	5.4	—	—	—	—	—	52.0	8.4	29.0	23.0	76.0
V	41	140	15	23	101	54	30	143	58	45	24	68	140	284
Y	6	19	15	85	—	—	—	—	—	23	10	26	104	14
Zn	362	258	197	1 855	403	70	70	77	210	349	111	158	462	156
Zr	5	6	5	23	56	31	22	52	37	—	—	—	—	135
Sb	—	—	—	—	5.0	5.0	25.0	5.0	5.0	—	—	0.5	—	—
As	108.0	19.0	0.7	217.0	197.0	49.0	761.0	59.0	40.0	—	6.3	16.0	—	43.0
Cd	0.1	0.1	0.1	5.6	7.0	5.0	7.0	5.0	5.0	—	0.1	0.3	0.9	0.6
Ce	204.0	12.0	4.0	29.0	—	—	—	—	—	23.0	5.3	42.0	76.0	23.0
Ga	8.20	11.00	8.60	20.00	—	—	—	—	—	2.20	0.84	4.50	2.90	9.70
La	127.0	6.0	22.0	14.0	—	—	—	—	—	7.0	3.3	23.0	52.0	11.0
Pb	181.0	12.0	4.0	15.0	25.0	49.0	82.0	67.0	12.0	4.8	56.0	11.0	4.5	33.0
Mo	1.8	5.4	1.1	23.0	13.0	5.0	79.0	8.0	5.0	1.1	0.6	0.5	0.5	2.5
Nb	1.2	0.6	0.5	1.8	—	—	—	—	—	5.9	0.5	6.2	4.0	3.9
Rb	3.70	3.50	1.00	17.00	—	—	—	—	—	1.23	0.38	1.20	1.30	5.50
Se	—	—	—	—	—	—	—	—	—	2.9	1.0	3.3	3.2	7.4
Ag	0.09	—	—	—	<1	<1	<1	<1	—	0.22	—	0.18	—	0.17
Sr	37.0	6.6	3.5	9.4	—	—	—	—	—	2.0	4.3	60.0	9.3	13.0
Th	5.30	1.40	0.60	2.40	—	—	—	—	—	1.15	0.58	0.80	0.62	34.00
Sn	0.5	0.4	0.4	0.4	—	—	—	—	—	1.6	2.2	9.7	2.6	3.5
W	3.5	1.4	1.0	1.0	9.0	5.0	9.0	5.0	9.0	2.9	0.1	1.2	1.5	0.4
U	.90	1.00	0.11	16.00	—	—	—	—	—	2.00	1.03	1.25	0.26	1.95
S	2 200.00	700.00	100.00	900.00	1 400.00	1 030.00	344.00	172.00	1 590.00	0.01	0.20	0.47	0.05	0.06
Ba	4 477	156	132	373	1 190	2 430	197	575	6 050	28	31	83	42	199

- NOTES:**
- (a) Gossan in black shale
  - (b) Gossan
  - (c) Ferruginous quartz
  - (d) Ferruginous quartz vein
  - (e) Gossanous siltstone
  - (f) Ironstone

Analyses performed at AMDEL, using ICP and ICP-MS after a mixed acid solution. Analyses of sample numbers P173143 to P173160 were kindly provided by Morning Star Resources. These analyses were performed at Australian Laboratory Services, using XRF spectrometry

**SOURCE:** Pirajno et al. (1998b)





**Figure 32. Idealized section through drillholes GD-1, GD-2, and GD-3, showing stratiform zone of alteration and weak sulfide dissemination (data from Guj and McIntosh, 1984)**

near the contacts with the Goodin Inlier contain anomalous Pt, Pd, V, and Cu (Table 4). Ferruginous quartz veins are associated with northwesterly trending faults and hosted in rocks of the Juderina Formation in the north-western part of MOOLOOGUOL. They contain slightly elevated values of Cu and Zn (Table 4).

Minor sulfide mineralization is locally evident in the dolerite of the Killara Formation, in the form of veinlets and disseminations of pyrite and chalcopyrite. The chalcopyrite is spatially associated with magnetite, now altered to leucoxene. Pyrite veinlets follow boundaries between plagioclase and clinopyroxene. This mineralization, in association with the development of a quartz–epidote vein assemblage, suggests limited hydrothermal activity.

The black argillites in the Johnson Cairn and Maraloo Formations of the Yerrida Group, particularly in the southern part of MOUNT BARTLE, are locally anomalous in copper (up to 2800 ppm), zinc, and mercury (Drummond, 1984). Drillcore intersections of these thick, black carbonaceous argillite units, and of evaporitic chert – carbonate breccia of the Bubble Well Member, contain hydrocarbon residues (Drummond, 1984). These hydrocarbons were possibly derived from the carbonaceous units, with some residue retained in interstices in the evaporitic dolostones of the Bubble Well Member.

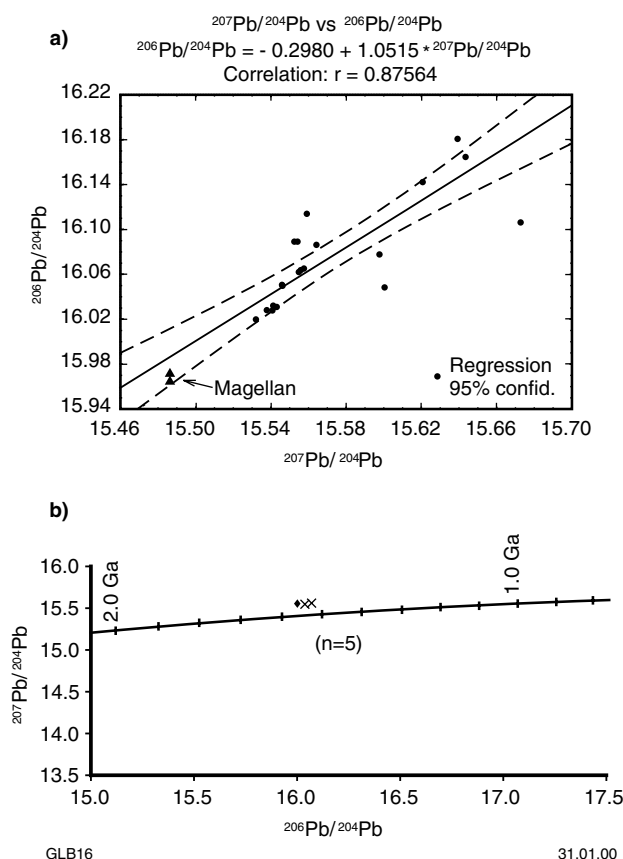
The formation and migration of petroleum as a consequence of the burial and maturation of organic-rich source rocks are well documented in Palaeoproterozoic sequences (Dutkiewicz et al., 1998). Hydrocarbon residues in carbonate breccias, possibly similar to those of the Yerrida succession, are recorded in association with base metal deposits from the Transvaal Sequence in South Africa (Roberts et al., 1993) and from the Palaeozoic Lennard Shelf, Canning Basin, northwestern Australia (Eisenlohr et al., 1994).

Two molybdenum lithogeochemical anomalies were located about 5 km apart and just above the Yerrida–Earaheedy unconformity. These sites are in the low range of hills south-southwest of Crystal Well on Paroo Station. Trace-element analysis of a quartz vein sample gave 2830 ppm Mo. A sample of lateritic ironstone, capping rubbly stromatolitic dolomite of an outlier of the Yelma Formation (Earaheedy Group) was analysed at 1090 ppm Mo. The latter site lies a few tens of metres east of the base of a northerly trending gully that may be fault controlled. The Earaheedy unconformity is exposed on the western flank of this assumed fault. The origin of these molybdenum anomalies in rocks of the Earaheedy Group is not known, but they may be related to faulting.

The Magellan lead deposit, situated in the southeastern part of the Yerrida Basin, is hosted in an outlier of the Yelma Formation, but the mineralization transgresses the unconformity into the upper layers of the Maraloo Formation. The discovery of the Magellan deposit was announced by Renison Goldfields Consolidated in 1993. Its global resources are estimated at approximately 220 Mt at 2.2% Pb, but higher grade and potentially economic mineralization is restricted to small pods (Renison Goldfield Consolidated, 1995). Measured resources are estimated at 4.53 Mt at 7.8% Pb (indicated category) and 3.36 Mt at 4.5% Pb (inferred category), both using a 3% cut-off grade (McQuitty and Pascoe, 1998). The mineralization covers an area of approximately 5 by 2.5 km. The mineralized zone is in the form of a subhorizontal sheet, within 45 m of the surface.

The Magellan mineralization, consisting of lead carbonate (cerussite), oxide (plattnerite), and phosphate (pyromorphite), is hosted in silicified immature wacke and stromatolitic carbonate units of the Finlayson Member (Yerrida Group) and the unconformably overlying Yelma Formation (Earaheedy Group). The latter is present as scattered outliers within the Yerrida Basin (Fig. 1; Plate 1). One of the host rocks (immature wacke) is characterized by selectively pervasive sericitic and kaolinitic alteration. Details on the Magellan deposit can be found in McQuitty and Pascoe (1998) and Pirajno and Preston (1998).

The lead minerals are paragenetically late and present as a replacement mineral in the matrix of the host rock. Trace-element analyses of ore materials indicate anomalous abundances of barium (1000–1828 ppm), manganese (1900–3672 ppm), and copper (257–400 ppm). No sulfides or other metals are present. The lack of sulfides and the unique presence of oxide minerals would suggest that the deposit is the result of palaeoweathering processes, under physicochemical conditions that were conducive to the oxidation and subsequent mobilization of lead metal. The lead was possibly sourced from weathered basement rocks. This is supported by lead isotopic values ( $^{206}\text{Pb}/^{204}\text{Pb}$  of 15.97153 and 15.96831;  $^{207}\text{Pb}/^{204}\text{Pb}$  of 15.48658 and 15.48611;  $^{208}\text{Pb}/^{204}\text{Pb}$  of 35.35561 and 35.35841; D. Nelson, 1995, unpublished data; Fig. 33a; Le Blanc Smith et al., 1995). These data provided a Pb–Pb model age of the carbonate ore material of 1.65 Ga (Pirajno et al., 1995; Fig. 33b). The origin of the Magellan deposit remains unknown. It is possible, however, that this



**Figure 33. Lead-isotope plots showing: a)  $^{207}\text{Pb}/^{204}\text{Pb}$  versus  $^{206}\text{Pb}/^{204}\text{Pb}$  of Magellan ore and sulfide samples from Pb–Zn prospects located in the Yelma Formation (Sweetwaters Well Member) on NABBERU; and b) the Cumming and Richards (1975) ore lead-isotope evolution curve for lead minerals in the Magellan deposit**

unusual type of mineralization is associated with the migration of low-temperature late basinal fluids along permeable lithotypes. The only other record of a similar style of lead carbonate(–barite) mineralization is from Sardinia, Italy (Fadda et al., 1998). These authors considered this mineralization to be a red bed, sandstone-hosted, lead–barium deposit, whose origin may be related to an oxidizing and alkaline depositional and diagenetic environment. Cerussite and plattnerite are mineral phases that are stable under highly alkaline and oxidizing conditions (pH values ranging from about 8 to 10 at 1 bar and 25°C; Eh from 0 to +0.8; Krauskopf, 1979). The oxidation and carbonation of a sulfide-rich precursor is excluded because this would generate abundant  $\text{SO}_4^{2-}$ , which in turn would produce argillic alteration of the host rocks. Argillic alteration is not present either at Magellan or in the Sardinian deposit. The formation of cerussite is most probably linked to the presence of abundant  $\text{CO}_2$  in basinal brines and the leaching of lead and barium from oxidized and weathered sources, which in the Yerrida and Earahedy Basins are best accounted for by Archaean granite–greenstone rocks.

## Precious metals

Palladium anomalies in the regolith, along the western edge of THADUNA, and platinum anomalies in south-central THADUNA are associated with rocks of the Killara Formation. The area of platinum anomalies is associated with northerly trending gabbro units, suggesting possible magmatic segregation. The area of palladium anomalies is associated with a zone of intercalated Killara Formation units and sedimentary rocks of the Thaduna and Doolgunna Formations. Regional regolith geochemistry for the PEAK HILL 1:250 000 map sheet can be found in Subramanya et al. (1995).

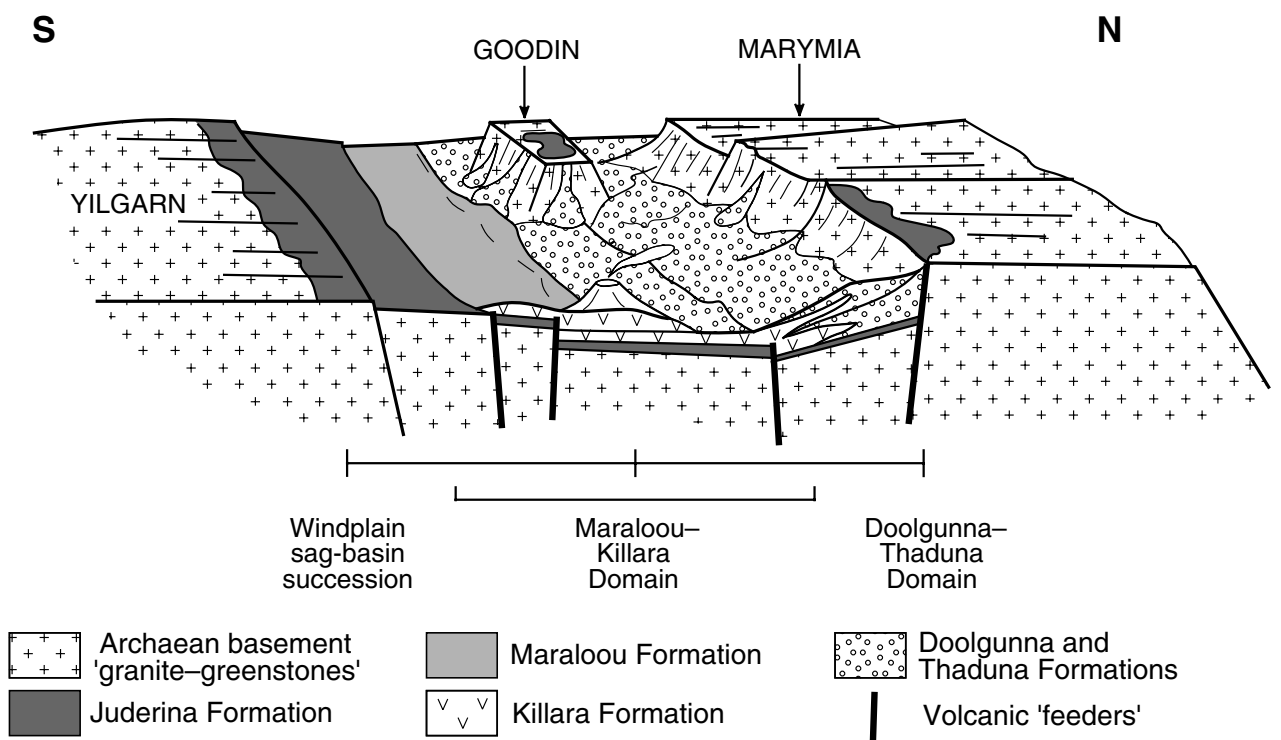
The presence on THADUNA of sulfides associated with kerogen in carbonate rocks of the Yelma Formation, and the platinum–palladium regolith anomalism associated with mafic rocks of the Killara Formation suggest that there is potential for carbonate-hosted Mississippi Valley-type base metal mineralization and mafic rock-hosted PGE mineralization.

The Goodin Find gold deposit is located approximately 80 km north of Meekatharra, near the Great Northern Highway. Gold mineralization at Goodin Find is within a shear zone subsidiary to the Goodin Fault. The mineralization is hosted in rocks of the Doolgunna Formation.

## Basin development and tectonic evolution

A model of the depositional setting of the Yerrida Group is shown in Figure 34. In this model the initial Yerrida Basin was formed in response to east–west transtensive movements that resulted in a pull-apart structure (Fig. 35a). This structure was probably controlled by easterly trending strike-slip fault systems. The dynamics of rift basins associated with strike-slip displacements are linked to variations along the trace of a regional fault. Thus, a ‘releasing bend’ leads to local extension along the fault zone. These localized fault zones of extension result in pull-apart basins (Allen and Allen, 1990).

In the region of the future Yerrida Basin, a phase of initial transtension created a sag basin. Pb–Pb dating of stromatolitic carbonate suggests that this sag phase occurred at approximately 2.1 Ga. The sag basin was filled by alluvial-plain siliciclastic sediments, and then coastal stromatolitic carbonate and evaporitic deposits (Juderina Formation, Windplain Subgroup; Fig. 35b). The evaporites are indicative of localized sabkha-like environments (?marine or ?lacustrine). The Juderina Formation is characterized by the association of siliciclastic (Finlayson Member) and evaporitic (Bubble Well Member) rocks. The predominantly fluvial clastic rocks of the Juderina Formation grade into the deeper water facies sedimentary rocks of the Johnson Cairn Formation. This association (siliciclastic–evaporitic–shale) is consistent with a strike-slip basin and early stages of continental rifting and breakup (Hardie, 1991). The Juderina Formation was



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**Figure 34. Tectonic setting for the Yerrida Basin and emplacement of the Killara Formation continental tholeiite**

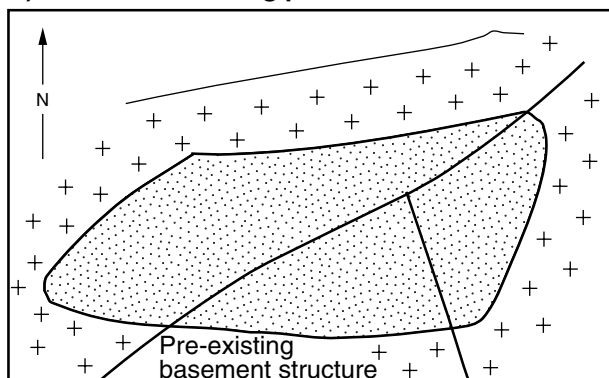
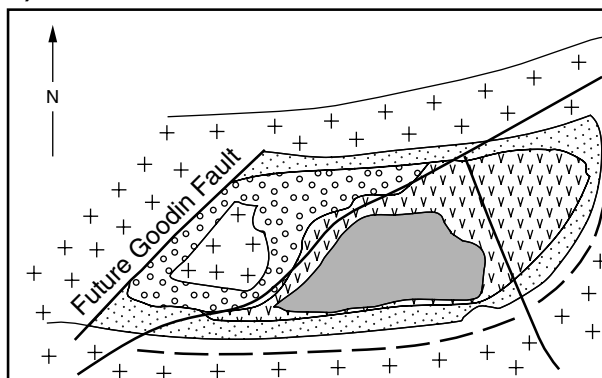
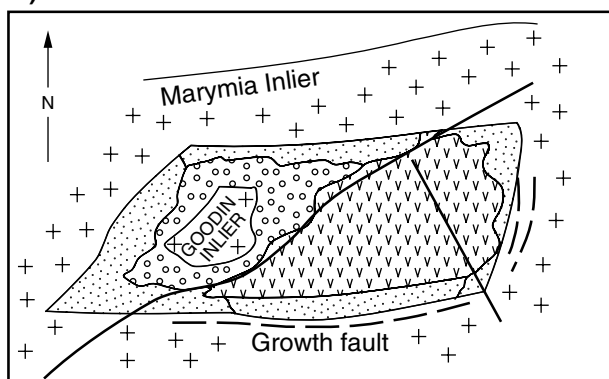
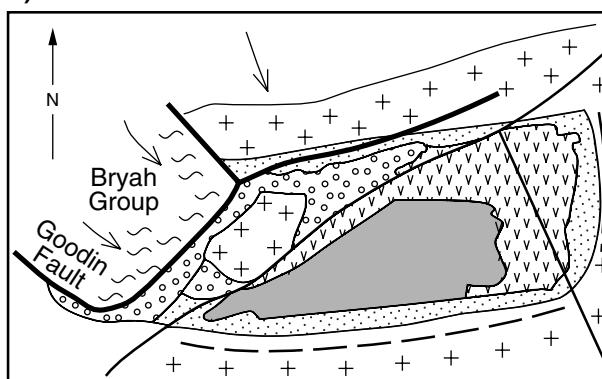
deposited on Archaean basement (Yilgarn Craton). The Goodin Inlier was part of this basement, but was later uplifted, its cover eroded and resedimented in surrounding sub-basins as part of the Mooloogool Subgroup. This is supported by sedimentological evidence from the diamictite units of the Doolgunna Formation, which contain exotic blocks of the Bubble Well Member (Adamides, 1998; Doolgunna graben of Pirajno, 1996).

Following the initial transtension, the sag-basin evolved into a rift-basin (Mooloogool rift) into which rocks of the Mooloogool Subgroup accumulated. This rifting event was associated in time and space with the extrusion of mafic lavas (Fig. 35c). Basin-margin growth faults had east, north-northwest and east-northeast orientations. This is suggested by the subparallel easterly trending mafic dykes in the south, the east-northeast alignment of dolerite sills and tholeiitic rocks northwest and southeast of the Yerrida Basin associated with volcanic centres (Plate 1), and the northwesterly trending geomorphological boundary on the southwestern side of the Kimberley Range. This boundary, which also marks the approximate contact between the Killara and Maraloou Formations, may reflect an original rift boundary, with the Maraloou Formation units indicating a quiet, euxinic-type environment (sulfidic shales of the Maraloou Formation). The Kimberley Range rift boundary was probably formed by reactivation of pre-existing structures of the Archaean Wiluna greenstone belt.

Voluminous and rapid outpouring of the continental tholeiitic lavas occurred in the newly formed rift structure, along easterly, north-northwesterly and east-northeasterly

trending fractures, making up a tilted T-shape pattern, as illustrated in Figure 35d. The eruption of mafic lavas was contemporaneous with the influx of turbiditic sediments (Doolgunna and Thaduna Formations; Fig. 35c). These sediments were sourced from the Marymia and Goodin Inliers, as well as from volcanic rocks. Examination of outcrops and petrographic studies suggest that the volcanic detritus was sourced from the greenstone rocks of the Marymia Inlier and the Killara Formation. Indeed, blocks of Killara Formation tholeiites are present in turbiditic rocks on the southeastern margin of the Goodin Inlier (Fig. 11). The eruption of the mafic lavas was then followed by sedimentation in stagnant and anoxic conditions (Maraloou Formation; Fig. 35). Thus, the deposition of the Mooloogool Subgroup was first characterized by high-energy conditions, suggesting an asymmetric rift basin surrounded on two sides, western and northern, by areas of uplift (Mooloogool rift; Pirajno et al., 1995). This was followed by a stagnant and anoxic environment, perhaps a lake, into which the Maraloou Formation shales were deposited.

An important point is that contrary to what is observed for the Yerrida Basin, many rift basins that form during continental extension are preceded by uplift and volcanism and commonly followed by an overlying sag phase (Etheridge et al., 1987). The sag phase is related to thermal relaxation and loading, which results in subsidence and accumulation of siliciclastic rocks. As proposed in the model of Figure 35, the Yerrida Basin was characterized by a sag phase followed by rifting and volcanism. This sequence of events supports the view that rifting was not due to thermal uplift and that the basin was formed

**a) Extension and sag phase****c) Rift basin****b) Rift basin****d) Rift basin**

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- Archaean granite-greenstone
- Windplain Subgroup  
Evaporites and siliciclastic arenaceous rocks  
(Juderina and Johnson Cairn Formations)
- Megabreccia and turbidites  
(Doolgunna and Thaduna Formations)

- Tholeiites  
(Killara Formation)
- Sedimentation of black shales  
(Maraloou Formation)
- Collision of Bryah and Yerrida Groups  
along Goodin Fault

**Figure 35. Stages in the geodynamic evolution of the Yerrida Basin as a pull-apart structure:**

- a) Sinistral strike-slip faulting produces a pull-apart basin at about 1.9 Ga. The new structure is at first a shallow basin (sag) in which siliciclastic rocks and evaporites are deposited;
- b) The sag structure evolves into a rift basin, with relative uplift of surrounding region. Sedimentation is now dominated by diamictite and turbidite rocks. At the same time, eruption of continental tholeiite begins mostly along northeasterly, easterly, and northwesterly trending faults;
- c) Volcanism wanes and deeper water sedimentation in an anoxic environment begins;
- d) At about 1.8 Ga, collision of the Pilbara and Yilgarn Cratons is nearly complete. The Bryah Group is thrust over the Yerrida Group along the Goodin Fault. This results in further sedimentation with influx of turbiditic rocks in a graben-like structure on the eastern side of the Goodin Fault

through far-field tectonics, namely a pull-apart resulting from strike-slip faulting.

At a later stage, the Bryah Group in the west collided with the Yerrida Group (east) along a northeasterly trending line, the future Goodin Fault (Fig. 34d). The Bryah Group was thrust over the Yerrida Group for a distance of at least 30 km, as indicated by the 'tails' of Juderina Formation that flank the Bryah Group to the southwest and northeast (Plate 1). This resulted in strong deformation (and uplift) along the northwestern margin

of the Yerrida Basin, in front of an advancing fold-and-thrust belt (Bryah Group). The precise timing of the collision is not known, but it is possible this is part of the tectonic events that occurred along the northern margin of the Archaean Yilgarn Craton during the c. 1.8 Ga Capricorn Orogeny (Tyler and Thorne, 1990; Tyler et al., 1998), which was the result of oblique convergence and collision of the Yilgarn and Pilbara Cratons.

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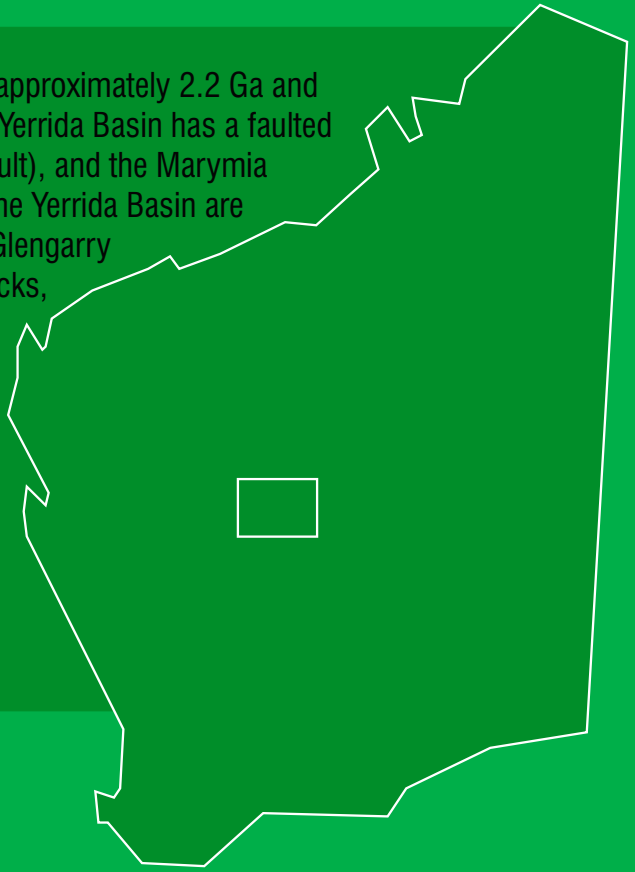
## Appendix

### Gazetteer of localities

	<i>AMG coordinates</i>	
	<i>Easting</i>	<i>Northing</i>
Bobs Bore	780100	7103600
Browny Bore	721250	7109500
Cave Hill	708800	7115300
Centre Pool Bore	709000	7124400
Clarrie Well	768950	7071700
Cookies Bore	772750	7088800
Cork Tree Bore	760150	7154800
Corner Well	772800	7082250
Crystal Well	766050	7093850
Daulby Well	682300	7108350
Desert Well	713350	7074800
Diamond Well Homestead	753450	7101050
Diamond Well	757550	7103200
Divide Bore	736300	7108300
Edingunna Spring	771600	7158300
Freshwater Well	798800	7156300
Goodin Find gold deposit	692500	7126510
Goosie Bore	822490	7074500
Granite Bore (Mooloogool area)	727400	7133800
Green Dragon opencut	774646	7180920
John Bore	734800	7164100
Johnson Cairn hill	771557	7184309
Juderina Bore (on DOOLGUNNA)	729900	7146900
Karalundi Homestead	668000	7108850
Killara Homestead	695300	7084100
Lanagan Bore	820390	7044400
Lee (Ricci) deposit	771000	7173500
Little Well	775000	7164500
Magellan lead deposit	793199	7063287
Maraloou Well	761150	7078100
Mooloogool Homestead	709250	7110900
Mount Alice	822640	7079500
Mount Leake Bore	714100	7147500
Mount Russell	783400	7066050
Mug Well	782300	7086500
No. 1 Bore	734400	7153900
No. 8 Bore	755750	7099250
North Bore	700200	7091700
North Well	706500	7092800
Paroo Homestead	776150	7092250
Quartermaine Well	796800	7126600
Rainlover Well	710300	7093400
Randal Bore	691620	7103000
Referendum Bore	694600	7086700
Rockhole Bore	713900	7091500
Rooneys mine	771100	7180600
Thaduna copper mine	772731	7176064
Top Kukabubba Well	822500	7087700
Utahlarba Spring	723250	7116000
White Well	779410	7084000
Willie Well	797100	7067000
Yandil Homestead	781750	7081150
Yerrida Spring	776000	7137400



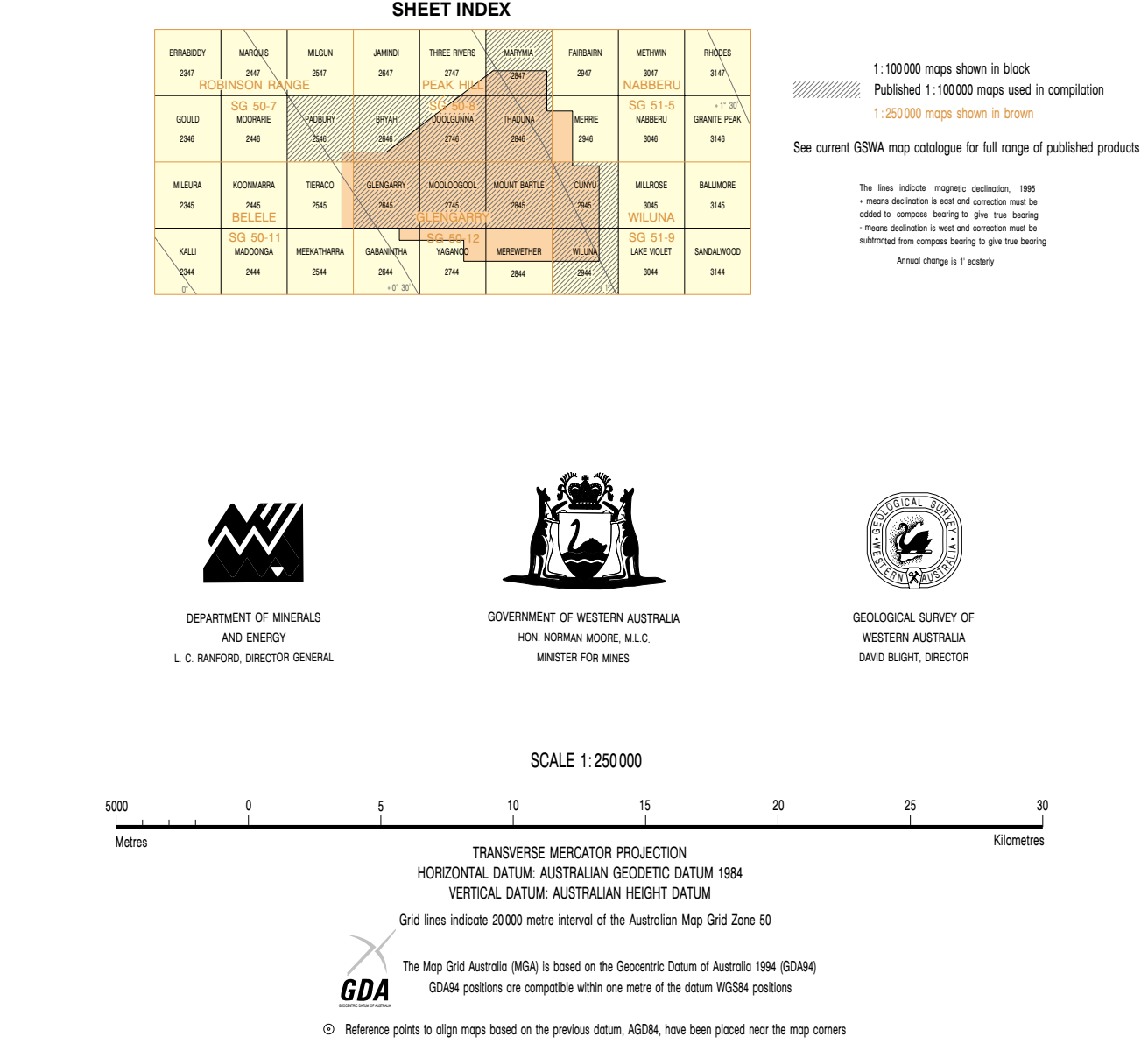
The Palaeoproterozoic Yerrida Basin was formed at approximately 2.2 Ga and was affected by the 1.8 Ga Capricorn Orogeny. The Yerrida Basin has a faulted contact with the Bryah Basin in the west (Goodin Fault), and the Marymia Inlier in the north. Rocks that have accumulated in the Yerrida Basin are assigned to the Yerrida Group (formerly part of the Glengarry Group). The Yerrida Group comprises siliciclastic rocks, evaporites, argillites, turbidites, continental tholeiitic basalts, chert units, sulfidic shale, and laminated siltstone. These rocks were deposited in shallow epicontinental seas, rift structures, and lacustrine environments. Known mineralization consists of shear zone-hosted copper deposits, quartz veins containing base metals, black shale-hosted barium, copper, platinum-group elements, and a large lead–carbonate deposit (Magellan).



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