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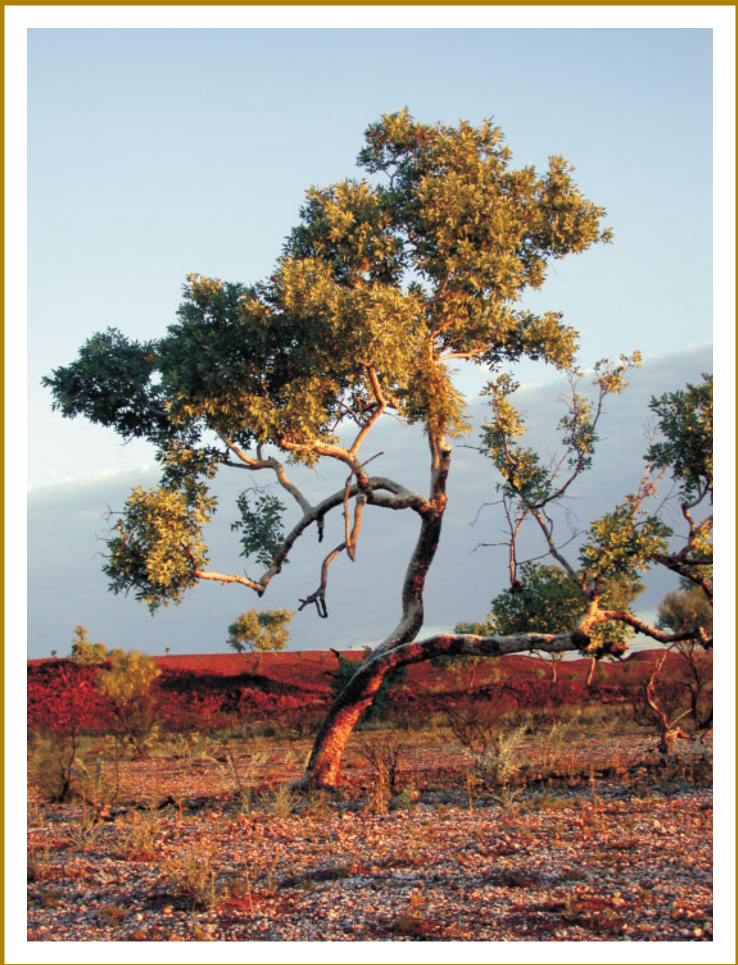
EXPLANATORY NOTES

GEOLOGY OF THE LAMIL 1:100 000 SHEET

by L. Bagas

1:100 000 GEOLOGICAL SERIES



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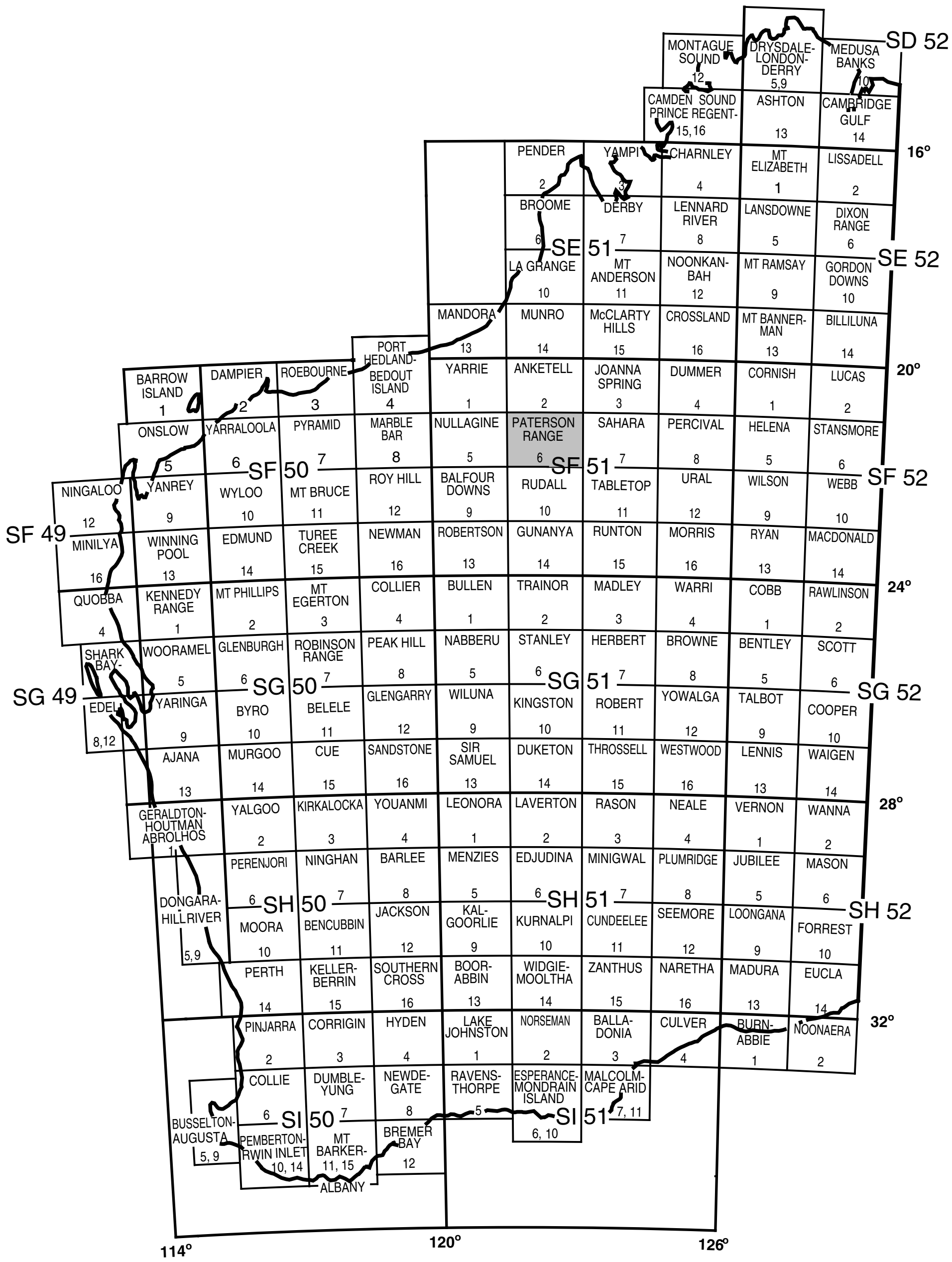

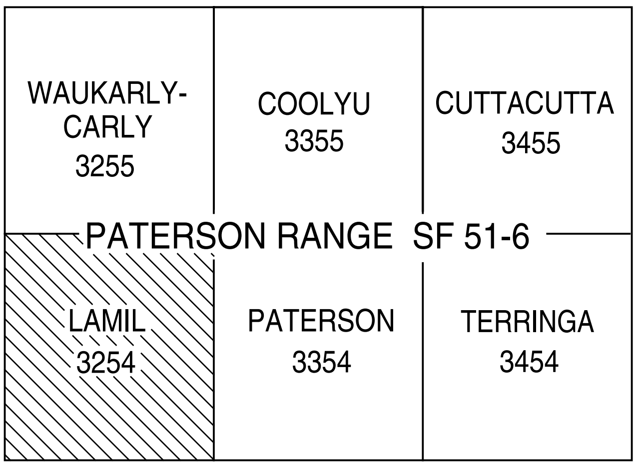

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GEOLOGICAL SURVEY OF WESTERN AUSTRALIA

GEOLOGY OF THE LAMIL 1:100 000 SHEET

by
L. Bagas

Perth 2005

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Cover photograph:
Throssell Range about 12 km south-southwest of the Nifty copper deposit (MGA 348650E 7591950N), Great Sandy Desert

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Geology of the Lamil 1:100 000 sheet

by

L. Bagas

Abstract

The LAMIL 1:100 000 sheet, occupying the northwestern part of the Paterson Orogen, comprises the Neoproterozoic Tarcunyah, Throssell Range, and Lamil Groups, and includes local outliers of sedimentary rocks of the Phanerozoic Canning Basin. The Paterson Orogen is a southeasterly trending belt of Proterozoic rocks that extends about 1200 km across the central part of Western Australia.

The Tarcunyah Group is part of the northwestern extension of the Officer Basin, and is correlated with Supersequence 1 of the Centralian Superbasin. On LAMIL, the group consists of the basal Googhenama Formation, Waroongunyah Formation, Brownrigg Sandstone, and Yandanunyah Formation, which are unconformable on the eastern margin of the Pilbara Craton.

The Throssell Range Group consists of the siliciclastic Coolbro Sandstone, and conformably overlying carbonaceous-rich Broadhurst Formation. The group is faulted against the Tarcunyah Group along the Vines Fault.

The Lamil Group is a sandstone–shale–carbonate succession that consists of the Malu, Puntapunta, and Wilki Formations. The group is younger than c. 1070 Ma, and is intruded by post-orogenic I-type monzogranites and syenogranites, which have SHRIMP U–Pb titanite crystallization ages of c. 654 Ma.

The c. 720 Ma Miles Orogeny is the first orogenic event recorded on LAMIL. The orogeny produced northwesterly trending folds and faults in the Tarcunyah, Throssell Range, and Lamil Groups, and locally developed thrusts and recumbent folds in the Throssell Range Group.

Structures associated with the c. 550 Ma Paterson Orogeny consist of north to northwesterly striking dextral faults (such as the Vines Fault), and east-northeasterly striking sinistral faults. These near-vertical conjugate strike-slip faults indicate south-southwesterly directed shortening.

A late brittle deformation event has been recognized in the Throssell Range. This event is younger than the Paterson Orogeny, and older than the Carboniferous–Permian Paterson Formation.

Carboniferous–Permian fluvioglacial sedimentary rocks unconformably overlie Proterozoic rocks in the southern half of the map sheet area. These form part of the poorly exposed Canning Basin succession that covers about half of the sheet under a Cainozoic veneer.

LAMIL is prospective for gold and base metal mineralization. The area contains the Nifty mine, which had produced over 150 000 t of copper by the end of 2003. There are also remaining oxide resources and an undeveloped copper sulfide resource estimated to contain a total of about 1.9 million tonnes of copper. The Nifty project has total oxide and sulfide resources of 148 million tonnes grading 1.3% Cu.

KEYWORDS: Paterson Orogen, Neoproterozoic, Tarcunyah Group, Throssell Range Group, Lamil Group, geological structures, mineralization.

Introduction

The LAMIL* 1:100 000 geological sheet (SF 51-6, 3254) covers the southwestern part of the PATERSON RANGE 1:250 000 sheet (SF 51-6), between latitudes 21°30' and 22°00'S and longitudes 121°30' and 122°00'E (Fig. 1). The sheet area is situated in the northwestern Paterson Orogen (Williams and Myers, 1990), and the southwestern part of the Canning Basin. LAMIL is included in the Marble Bar District of the Pilbara Goldfield.

Access, climate, and vegetation

The Nifty copper mine lies in the northwestern part of LAMIL. A good graded road, used for ore cartage and transporting mine supplies, links the mine with the Woodie Woodie manganese mine to the west on the NULLAGINE 1:250 000 sheet. Another well-formed gravel road in the northeastern part of the sheet area links Telfer with the Port Hedland – Woodie Woodie road to the west. Exploration tracks shown on the map sheet provide good access to the rest of the area.

The region has an arid climate with a mean annual rainfall of approximately 220 mm. The rainfall is erratic and the area is subject to long periods of drought as well as localized flooding during cyclonic and thunderstorm activity between December and April. Average daily summer temperatures range from minima of about 25°C to maxima of 40°C, whereas average daily winter temperatures typically vary between minima of 5°C and maxima of 25°C (Pink, 1992). Average annual evaporation is about 4000 mm and prevailing winds are from the east and southeast (Pink, 1992).

LAMIL is in the western part of the Great Sandy Desert botanical district of Beard (1975). Spinifex (*Triodia*) is present across the entire area, whereas other forms of vegetation are associated with different types of terrain. For example, sandplains also contain *Grevillea*, wattles (*Acacia*), soft shrubs (*Crotalaria*), eucalypts, and tea tree (*Melaleuca*). Creeks, such as those around the Throssell Range, contain grasses and large eucalypts such as Snappy Gum (*Eucalyptus brevifola*) and Bloodwood (*Eucalyptus dichromophloia*). Playa-lake margins contain saltbush (*Hemichron*, *Bassia*, *Frankenia*), samphire (*Arthrocnemum*), and spinifex. Areas of rock outcrop support small shrubs, grasses, mulga, and stunted eucalypts, whereas areas of colluvium generally contain spinifex, small shrubs, grasses, and *Acacia*. River Gum (*Eucalyptus camaldulensis*) and paperbark (*Melaleuca* sp.) line the larger drainage systems around Lamil Hills and Throssell Range (Beard, 1975).

Physiography

Old land surface

Carboniferous–Permian glaciation is a significant geological event that affected the physiography of LAMIL. Carboniferous–Permian palaeovalleys containing remnants of fluvioglacial sediments of the Paterson Formation are found as benches and rare mesas in the southwestern and eastern parts of LAMIL (Fig. 2).

Cainozoic palaeovalleys containing calcrete valley-floor deposits in the eastern half of the map sheet pre-date the sandplains that partially cover them, and are probably related to southeast-trending channels and lakes that were active during the early part of the Cainozoic. These deposits form low mounds in low-lying areas, and are composed of massive, nodular, and vuggy limestone that is partly replaced by chalcedony.

Recent land surface

Cainozoic erosion and deposition are significant geological events that have affected the physiography of LAMIL.

Erosional

The recent erosional land surface units represent various stages of erosion of older units. The low hills and range units rise up to 100 m above the sandplains (Fig. 2), and represent an advanced stage in the formation of a new peneplain. Erosion is restricted to wind action and water movement in small streams. Granite, carbonate, siltstone, and shale typically underlie low hills areas, and sandstone typically underlies the range unit.

Depositional

LAMIL contains sandplains that form the western part of the Great Sandy Desert, including longitudinal (seif) dunes and minor areas of dune-free sandplains, which together cover about three quarters of the sheet area (Fig. 2). The seif-dune sandplains are predominantly flat with westerly to northwesterly trending longitudinal dunes that are many kilometres long, up to 3 km apart, and have an average height of 12 m. The longitudinal profiles are consistent with prevailing winds from the southeast. Many of the dunes are asymmetrical with steeper southern slopes. The dune-free sandplains are subject to periodic flooding. The scree and outwash fan units, and the mixed eolian sandplain with playa lakes or claypans units, commonly flank sandplains, and represent locally derived clastic detritus from streams and channels that drain the old land surface. Recent alluvial channels dissect some of these deposits.

Previous investigations

Mineral exploration on LAMIL was extremely limited until 1971, when the Telfer gold deposit was discovered on PATERSON. Subsequently, many mineral exploration companies have explored the region including LAMIL (Chin et al., 1982; Tyrwhitt, 1995).

The Geological Survey of Western Australia (GSWA) carried out reconnaissance mapping of the PATERSON RANGE 1:250 000 sheet between 1974 and 1977 as part of the systematic 1:250 000 geological mapping of Western Australia (Trendall, 1974; Chin et al., 1982).

* Capitalized names refer to standard map sheets. Where 1:100 000 and 1:250 000 sheets have the same name, the 1:100 000 sheet is implied unless otherwise indicated.

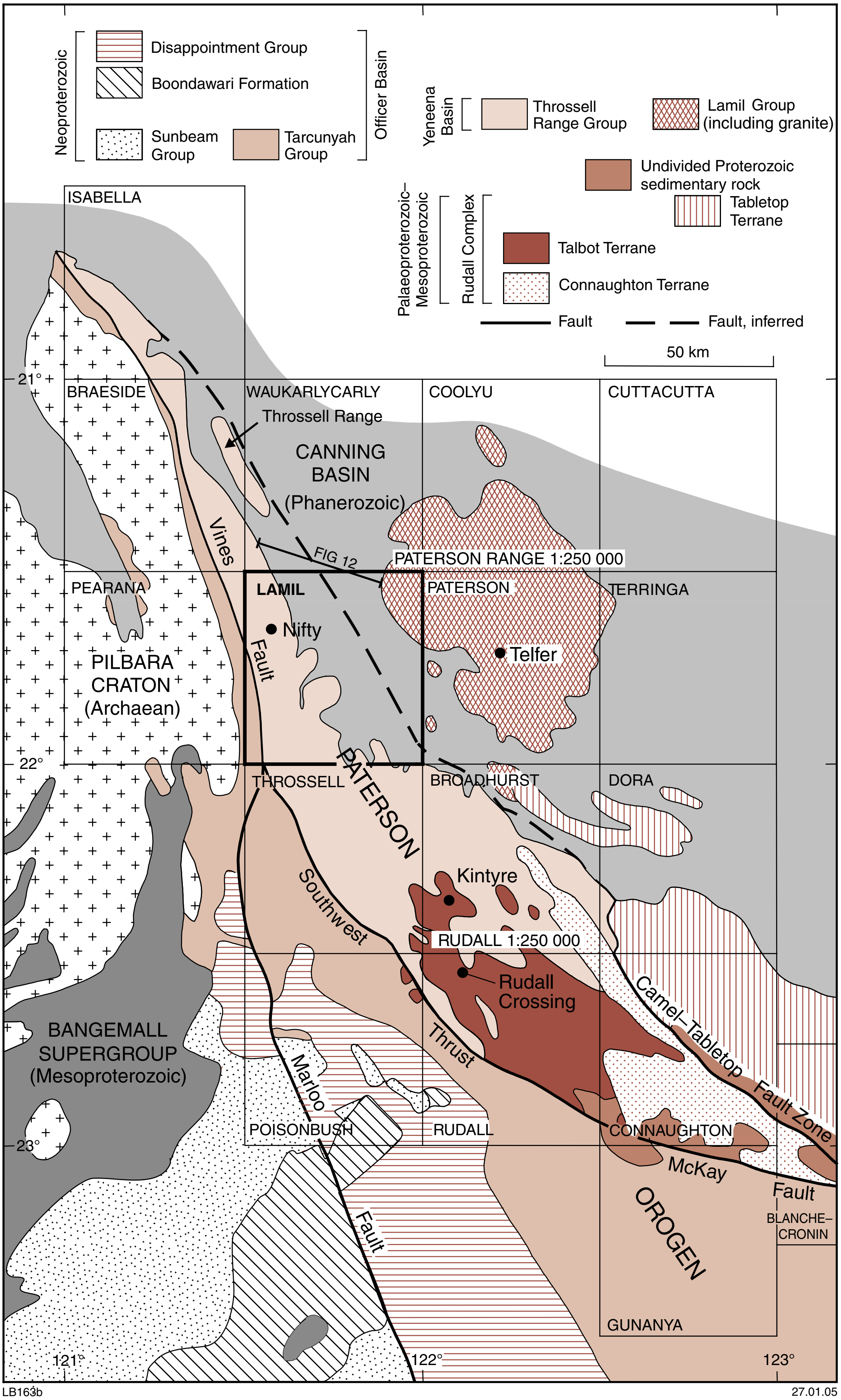

Figure 1. Regional geological setting of LAMIL (modified after Bagas, 2000). Also shown is the location of Figure 12

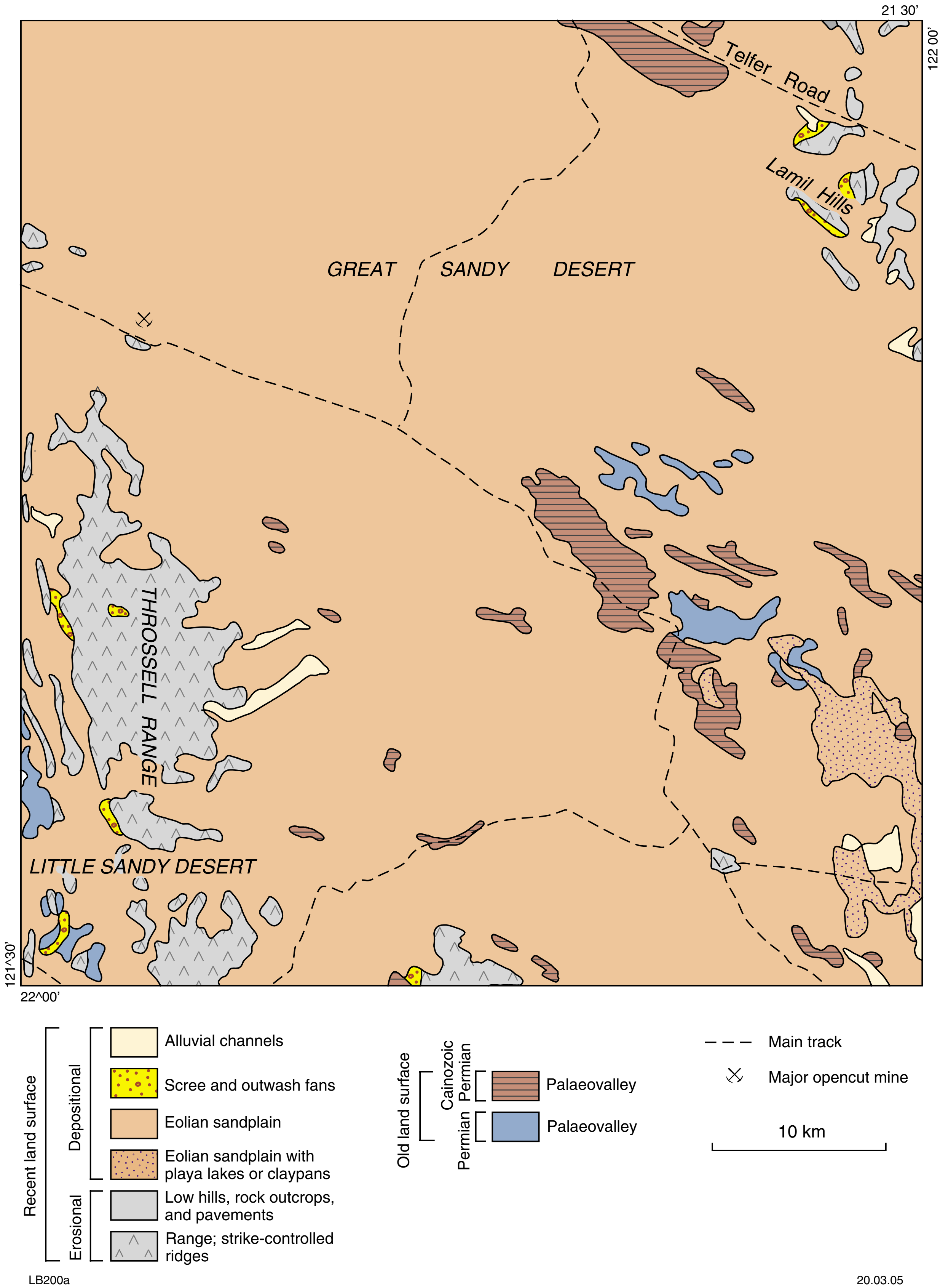

Figure 2. Physiography and access on LAMIL

Western Mining Corporation Ltd (now WMC Resources Ltd) discovered the Nifty deposit in 1981 during field investigation based on a conceptual model that the area was favourable for stratiform copper mineralization (Haynes et al., 1993). Mining of the Nifty deposit began about 1994. In 1998, WMC sold the deposit to Straits Resources, which in turn sold it to Birla Minerals Pty Ltd of the Aditya Birla Group of companies in 2003.

In 1989, GSWA commenced a detailed 1:100 000-scale geological mapping program of the northwestern Paterson Orogen. Maps and accompanying explanatory notes published as part of the project are: BROADHURST (Hickman and Clarke, 1994), GUNANYA (Bagas, 1998), CONNAUGHTON (Bagas and Smithies, 1998), RUDALL (Hickman and Bagas, 1998), THROSSELL (Williams and Bagas, 1999), BLANCHE–CRONIN (Bagas, 1999), POISONBUSH (Williams and Bagas, 2000), RUDALL 1:250 000 (Bagas et al., 2000), and PATERSON (Bagas, 2000). Figure 1 shows the location of these sheet areas.

This report and the accompanying LAMIL 1:100 000 geological map (Bagas, 2004a) are based on detailed regional mapping undertaken during 2002.

Regional geological setting

Williams and Myers (1990) defined the Paterson Orogen as ‘a belt of metamorphic, sedimentary, and igneous rocks that have a common tectonic history’. These metamorphosed Palaeoproterozoic to Neoproterozoic sedimentary and igneous rocks extend over 2000 km, from the northwest of Western Australia across the central part of Western Australia, into South Australia and the Northern Territory (Fig. 3). The rocks are exposed in the northwest along the eastern margin of the Archaean Pilbara Craton and in the Proterozoic Musgrave Complex of central Australia (Williams and Myers, 1990), and both areas were deformed during the c. 550 Ma Paterson and Petermann Orogenies (Williams and Myers, 1990; Bagas et al., 2002). The two exposed areas are connected in the subsurface by the Paterson–Musgrave structural link (Austin and Williams, 1978), recognized as a ‘gravity high’ known as the Anketell Regional Gravity Ridge (Fraser, 1976) or Warri Gravity Ridge (Iasky, 1990; Fig. 3).

Northwestern Paterson Orogen and southwestern Canning Basin

The northwestern Paterson Orogen was first referred to as the Paterson Province (Daniels and Horwitz, 1969; Blockley and de la Hunty, 1975). This part of the orogen is flanked to the west and southwest by the Precambrian West Australian Craton (Myers, 1990a), and to the east by the concealed North Australian Craton (Myers et al., 1996). The West Australian Craton is a combination of the Archaean Pilbara and Yilgarn Cratons sutured along the intervening Palaeoproterozoic Capricorn Orogen (Myers, 1990a; Myers et al., 1996; Cawood and Tyler, 2004). The craton is bounded to the north by the Phanerozoic Northern Carnarvon Basin, to the northeast by the Paterson Orogen, to the south and southeast by the Albany–Fraser Orogen, and to the west by the Pinjarra Orogen and Southern Carnarvon Basin. The North Australian Craton, which was probably accreted from older crustal fragments by c. 1830 Ma, is bounded to the southwest by the Paterson Orogen and to the east and northeast by the Tasman Line (Myers et al., 1996). The Tasman Line represents the easternmost extent of Precambrian basement against the Phanerozoic Tasman Orogen in the eastern part of Australia (Leven et al., 1998).

The northwestern Paterson Orogen is unconformably overlain to the northeast by the Phanerozoic Canning Basin (Middleton, 1990; D’Ercole et al., 2003). The orogen in this region includes the Palaeoproterozoic Rudall Complex (Williams, 1990a), Neoproterozoic Yeneena Basin (Throssell Range* and Lamil Groups), and Neoproterozoic Tarcunyah Group (Williams and Bagas, 1999) of the northwestern Officer Basin (Figs 1, 4, and 5).

The contact between the Tarcunyah and Throssell Range Groups is marked by the Vines–Southwest–McKay fault system located to the west of the Throssell Range, which extends over a strike length of 400 km (Fig. 1). These faults are long-lived structures that were probably active before deposition of the Tarcunyah and Throssell Range Groups. They were reactivated as thrust faults during the Miles Orogeny, as strike-slip faults during the Paterson Orogeny, and as normal faults during the Phanerozoic (discussed under **Structures associated with the Paterson Orogeny**). The fault system also coincides with the southwestern margin of the northwestern part of the Anketell Gravity Ridge (Fig. 3).

On the basis of geophysical data, the Throssell Range and Lamil Groups appear to have been juxtaposed along a major concealed northwesterly trending fault (Bagas, 2000), which is an extension of the long-lived Camel–Tabletop Fault Zone that was also active during the c. 550 Ma Paterson Orogeny (Bagas and Smithies, 1998) or later.

These major structures either played a major role in the deposition of the three groups or brought an exotic terrane containing the Throssell Range and Lamil Groups into contact with the Officer Basin to the west (Bagas et al., 2002). If the structures contributed significantly to the deposition of the groups, subsidence of, and deposition in, these intracratonic basins probably commenced during transpressional faulting that would have taken place during the onset of the Miles Orogeny.

The Canning Basin (Gentilli and Fairbridge, 1951) is named after the Canning Stock Route, and covers an onshore area of over 550 000 km^2 (Middleton, 1990). The basin developed in the early Palaeozoic and was an active depocentre during the Palaeozoic (Kennard et al., 1994); the Mesozoic to Cainozoic sediments within it are essentially veneers. During the basin’s Palaeozoic history, it has been subject to several major tectonic events that resulted in the formation of shelves, sub-basins, and a mid-basin ridge. These tectonic events include an initial extension during the Early Ordovician, compression

* Grey et al. (in prep.); previously referred to as the informally named Throssell Group.

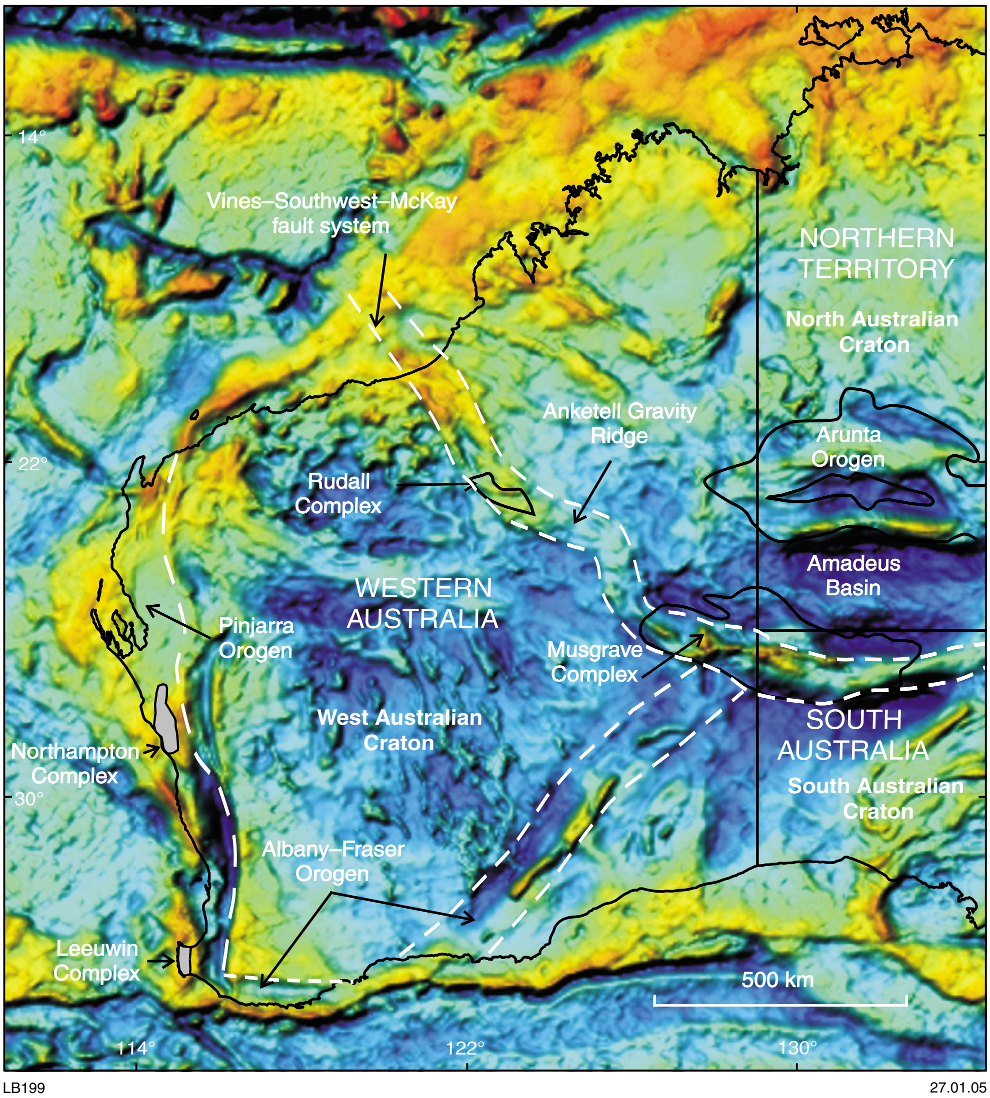

Figure 3. Gravity anomaly map of Western Australia (Murray et al., 1997) showing the location of the Anketell Regional Gravity Ridge, which approximately outlines the location of the Paterson Orogen

during the Silurian–Devonian Prices Creek Movement, the Devonian Pillara Extension, the Carboniferous Meda Transpression, and the Late Triassic Fitzroy Transpression (Kennard et al., 1994). The Silurian to Late Carboniferous events are synchronous with a series of events of compression and extension grouped in the c. 400–300 Ma Alice Springs Orogeny (Haines et al., 2001).

The Canning Basin is divided into the northwesterly trending Lennard and Billiluna Shelves in the north, the graben-like Fitzroy Trough and Gregory Sub-basin, the mid-basin Broome and Crossland Platforms, a broad downwarp that includes the Kidson and Willara Sub-basins, and the southern marginal Anketell and Ryan Shelves (Hocking et al., 1994). The southern margin is complicated by the development of northwesterly trending horst and graben structures including the Waukarlycarly Embayment, which is a poorly exposed trough with Carboniferous–Permian fill that extends through central LAMIL.

Structural history

Various authors have presented interpretations of the structural history of the Paterson Orogen (e.g. Chin et al., 1980; Myers, 1990a,b; Clarke, 1991; Hickman and Clarke, 1994; Hickman et al., 1994; Myers et al., 1996; Hickman and Bagas, 1998, 1999; Bagas and Smithies, 1998; Bagas et al., 2000; Bagas, 2000; Bagas, 2004b). These authors recognized two phases of Palaeoproterozoic deformation (D_1–D_2) in the Rudall Complex, which consists of multiply deformed and metamorphosed sedimentary and igneous Palaeoproterozoic and Mesoproterozoic rocks (Bagas, 2004b). They also recognized four phases of Neoproterozoic deformation (D_3–D_6). In addition to these events, one phase of Phanerozoic deformation (D_7) has been recognized in the Yeneena Basin on LAMIL.

The earliest (D_1 and D_2) deformation events recognized in the Rudall Complex are assigned to the

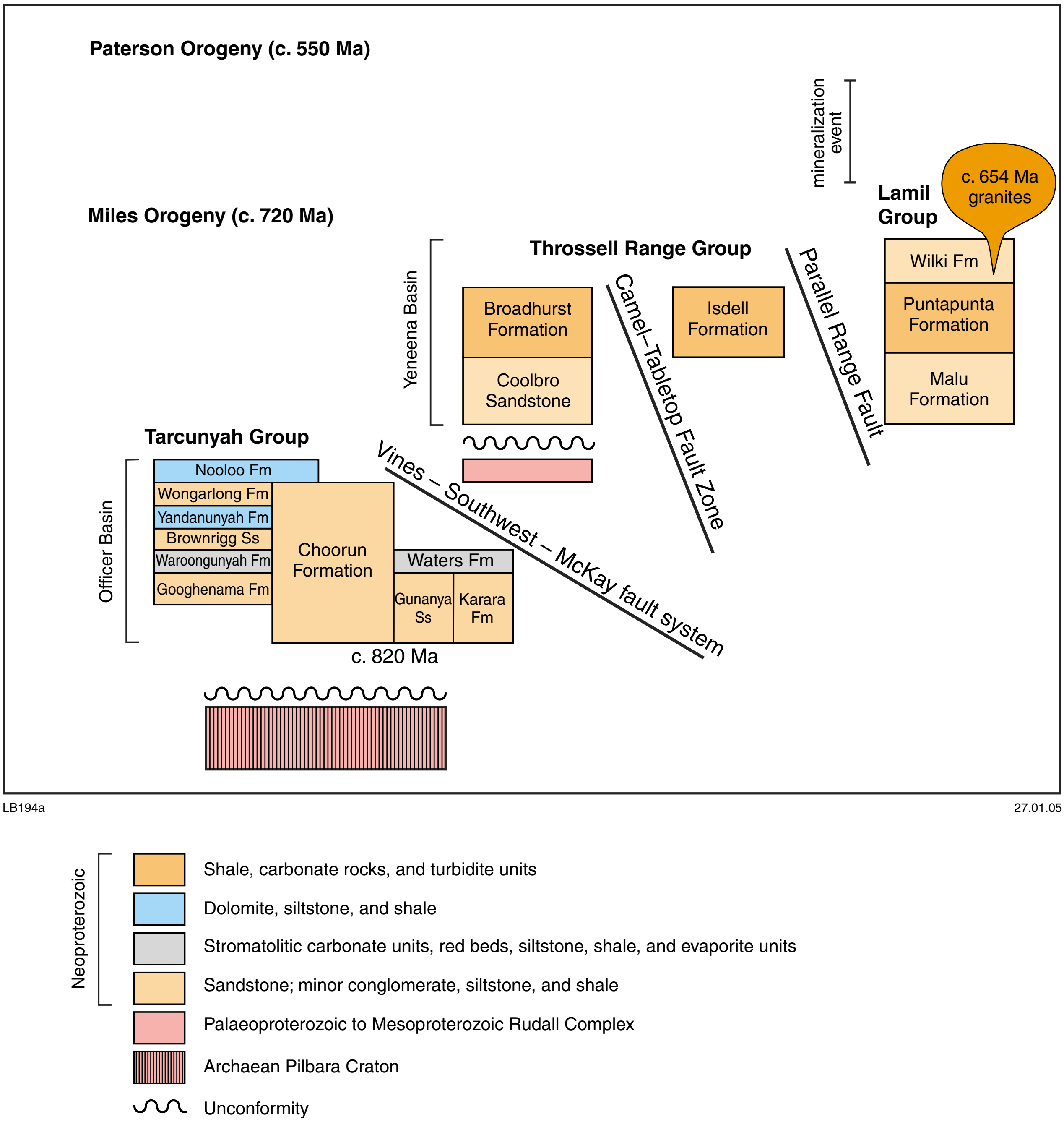

Figure 4. Simplified stratigraphy for the Neoproterozoic sequences of the Yeneena and northwest Officer Basins

Yapungku Orogeny (Bagas and Smithies, 1998). This Palaeoproterozoic orogeny represents a cycle of crustal thickening of about 35 km, as determined from pressure and temperature studies by Smithies and Bagas (1997), which is indicative of a major continent–continent collision.

Several northeast-trending open folds with southeasterly dipping axial planes and strike-slip faults have been mapped in Supersequence 1 of the northwestern Officer Basin (Williams and Bagas, 1999) and in the Rudall Complex (Hickman and Bagas, 1998). These structures, which indicate northwestern shortening against the Archaean Pilbara Craton, have been assigned to D_5, and have been associated with the Blake Movement (Williams, 1992). Williams (1992, 1994) interpreted the Blake Movement as a fault and fold event that resulted in basin inversion along the northwestern margin of the Officer Basin (former ‘Savory Group’) southeast of the Pilbara Craton. Deformation is characterized by steep reverse faults with transport directed toward the northwest. The Blake Movement may be a transpressional folding event associated with dextral strike-slip faulting (southwest block to the northwest) during the Paterson Orogeny (Bagas and Smithies, 1998).

A geological sketch of Neoproterozoic deformation events in the Throssell Range area is presented in Figure 6,

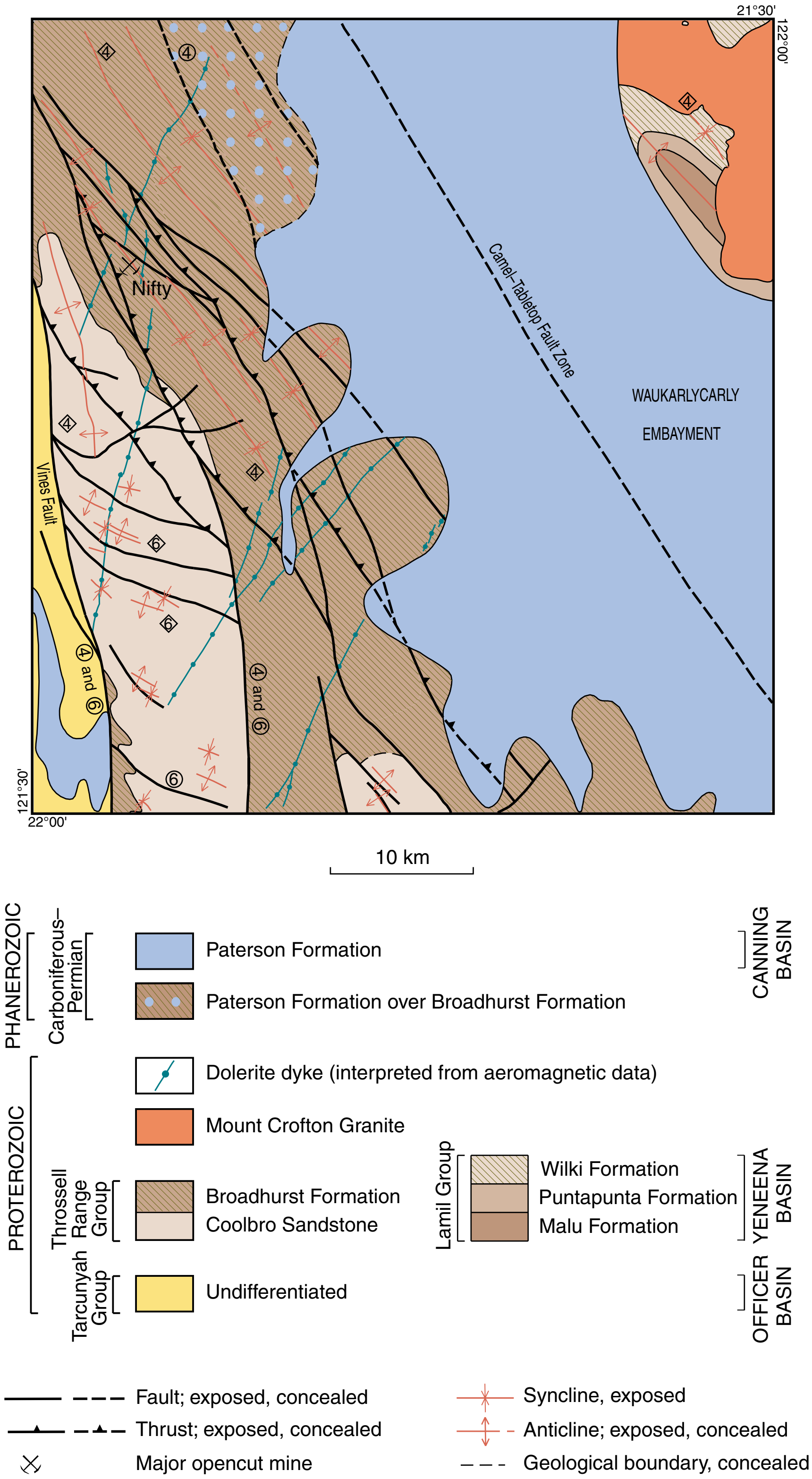

Figure 5. Simplified geological map of LAMIL, showing major structures

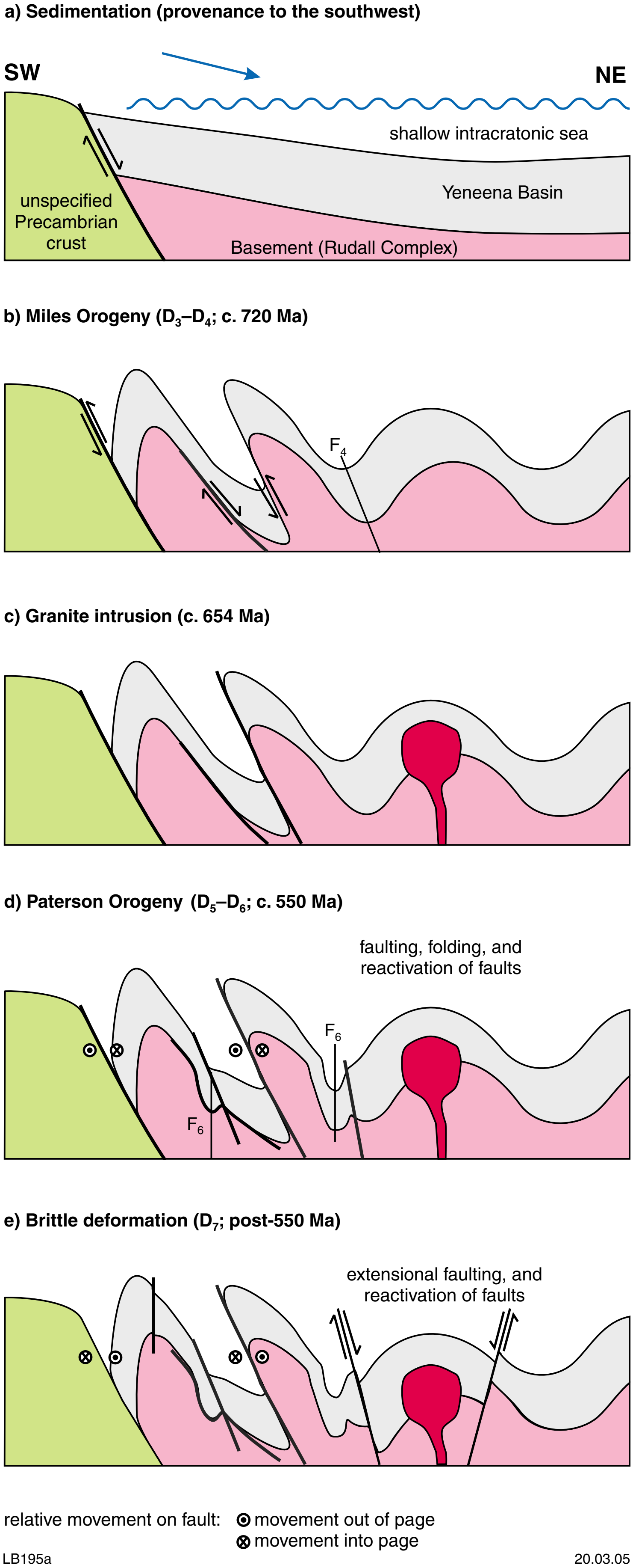

Figure 6. Geological sketch illustrating the structural evolution of the Neoproterozoic part of the northwest Paterson Orogen: a) Basin development and sedimentation with a southwestern provenance overlying the Rudall Complex; b) northeast–southwest compression during the c. 720 Ma Miles Orogeny, resulting in regional folding and an associated axial planar cleavage, and faulting; c) intrusion of granite at c. 654 Ma; d) north-northeast–south-southwest compression during the c. 550 Ma Paterson Orogeny, resulting in a dextral reactivation of northerly trending faults, tightening of earlier structures, and development of east-northeasterly trending folds and thrust faults; e) post-550 Ma deformation resulting in northeasterly trending dextral faults, and sinistral reactivation of northerly trending faults

Table 1. Summary of geological events on LAMIL (modified after Bagas, 2004).

Age range (Ma)	*Geological event*
c. 820–654[a]	Deposition of the Tarcunyah and Sunbeam Groups of the northwest Officer Basin, and the Throssell Range and Lamil Groups. The Tarcunyah Group is a supratidal to shallow-water and locally fluviatile–deltaic sequence. The Throssell Range and Lamil Groups are interpreted to have been deposited in transtensional basins
c. 750–720 (poorly constrained)	Approximate age for the southwesterly directed convergence associated with the **Miles Orogeny (D_{3-4})**, which was locally accompanied by lower greenschist metamorphism (M_4) and locally intense dynamic and hydrothermal metamorphism. This orogeny is in response to southwest-directed convergence
654–630	Emplacement of post-D_4 and pre-D_6 granites in the Lamil Group
c. 610 (poorly constrained)	**Blake Movement (D_5; Williams, 1992)**. These brittle structures recognized in the northwestern part of the northwest Officer Basin probably represent transpressional deformation associated with D_6 (Bagas and Smithies, 1998; Bagas, 2003)
c. 550	Approximate age for brittle deformation associated with the **Paterson Orogeny (D_6)**
?400–300	Brittle, northeasterly and northwesterly trending faults in Throssell Range and at Nifty, probably synchronous with the Alice Springs Orogeny

NOTE: (a) poorly constrained age range for the Throssell Range and Lamil Groups. The Tarcunyah Group is c. 820 Ma (Bagas et al., 1995, 1999)

and Table 1 summarizes the history of deformation and metamorphism on LAMIL.

Proterozoic rocks

The oldest rocks in the Paterson Orogen on LAMIL are Neoproterozoic in age, and consist of the Tarcunyah Group in the northwestern Officer Basin, the Throssell Range and Lamil Groups in the Yeneena Basin, and granitic rocks that intrude the Lamil Group at Mount Crofton.

Deposition of Neoproterozoic successions of fluviatile and shallow-marine sandstone, turbiditic sandstone, carbonate, siltstone, shale, evaporites, and minor conglomerate in the northwestern Officer Basin, Tarcunyah, Throssell Range, and Lamil Groups commenced c. 820 Ma (Fig. 4).

Officer Basin

The northwestern Officer Basin was originally regarded as the eastern part of the Mesoproterozoic 'Bangemall Basin' (Williams et al., 1976). It was elevated to separate basin status, as the Savory Basin (Williams, 1987), and its contents were named the Savory Group (Williams, 1992).

Bagas et al. (1995) proposed that the Tarcunyah Group, previously included in the Yeneena Basin (Williams, 1990b), is a correlative of the lower part of the Savory Group. They further proposed that the Tarcunyah and the lower Savory Groups are equivalent to Supersequence 1 of the Centralian Superbasin of Walter et al. (1995), and are part of the Officer Basin. The terms Savory Basin and Group were abandoned, the former lower Savory Group was renamed the Sunbeam Group, and the former upper Savory Group was renamed the Disappointment Group (Bagas et al., 1999). Grey and Stevens (1997) and Stevens and Grey (1997) used stromatolites and acritarch microfossils to strengthen the correlation of the Tarcunyah Group with Supersequence 1 of the Centralian Superbasin. Palynomorph taxa identified in the Tarcunyah Group include *Leiosphaeridia* sp., *Synsphaeridium* sp., *Arctucellularia ellipsoidea* and *Satka* sp. The stromatolites belong to the *Acaciella australica* Stromatolite Assemblage of Grey and Stevens (1997), which is c. 825 to 802 Ma in age (Grey et al., 2005).

Tarcunyah Group

The Tarcunyah Group (Williams and Bagas, 1999) unconformably overlies the southeastern part of the Pilbara Craton and the eastern part of the Bangemall Supergroup to the southwest of LAMIL (Williams, 1989), and overlies the Rudall Complex on THROSSELL and POISONBUSH to the south of LAMIL (Williams and Bagas, 1999, 2000). The concealed Vines Fault separates the Tarcunyah Group on the western edge of LAMIL from the Neoproterozoic Throssell Range Group to the east (Bagas et al., 2000).

The stratigraphic relationship between the Officer and Yeneena Basins remains uncertain. The Throssell Range and Lamil Groups might be equivalent to Supersequence 1 or 2 of the Centralian Superbasin, based on a provenance study using sensitive high-resolution ion microprobe (SHRIMP) U–Pb detrital-zircon age distributions by Bagas et al. (2002).

In stratigraphic order from oldest to youngest on LAMIL, the Tarcunyah Group consists of the Googhenama Formation, Waroongunyah Formation, Brownrigg Sandstone, and Yandanunyah Formation (Fig. 4). The following is a brief description of these formations.

Googhenama Formation (P̶ug-sp)

The Googhenama Formation (*P̶Ug*; Williams, 1990b) is estimated to be up to 500 m thick and unconformably overlies Archaean rocks of the Pilbara Craton on PEARANA to the west of LAMIL (Williams and Trendall, 1998). The formation is a fluviatile succession consisting of interbedded fine- to coarse-grained, light-pink to purple coloured sandstone, and granular to boulder conglomerate (*ᵽUg-sp*). The conglomerate is lenticular, commonly matrix-supported, and quartz-pebble rich or polymictic. Polymictic conglomerate beds contain granitic, vein quartz, chert, quartzite, sandstone, and rare jasper clasts. The sandstone units are commonly quartz rich, with trough cross-laminations and ripple marks, suggesting a western provenance.

Waroongunyah Formation (ᵽUw-ss)

The Waroongunyah Formation (*ᵽUw*; Williams, 1989) conformably overlies the Googhenama Formation on southwestern LAMIL. The formation is about 600 m thick and contains rarely exposed dolomite interbedded with pink to grey-white siltstone and shale, and thin beds of brown, fine-grained sandstone containing scattered halite pseudomorphs (*ᵽUw-ss*). The dolomite is massive to laminated, locally stromatolitic, commonly silicified and oolitic, and sandy in places. The formation is a transgressive shallow-marine sequence probably deposited shorewards of carbonate build-ups (Williams and Trendall, 1998). These may have been barrier islands or carbonate platforms marginal to the Pilbara Craton (Williams and Bagas, 1999).

Brownrigg Sandstone (ᵽUr-stq)

The Brownrigg Sandstone (*ᵽUr*; Williams, 1989) is at least 600 m thick (Williams and Bagas, 2000) and is exposed west of the concealed Vines Fault on southwestern LAMIL. The formation consists of white, cream to light brown, fine- to coarse-grained quartz sandstone with cubic and spherical voids after pyrite and limonite, and scattered, small pebbles of vein quartz (*ᵽUr-stq*). The formation is well bedded with alternating flaggy and massive beds (Fig. 7). Cross-lamination with sets up to 3 m thick

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Figure 8. Cross-bedded, pebbly sandstone containing rounded quartz pebbles in a poorly sorted matrix of the Brownrigg Sandstone (MGA 345850E 7583950N)

(Fig. 8), ripple marks, and current striae are common. The palaeocurrent direction is commonly towards the northeast and east. The formation is probably a shallow-marine shelf deposit (Williams and Bagas, 2000).

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Figure 7. Well-bedded and flaggy sandstone of the Brownrigg Sandstone (MGA 348250E 7578690N)

Yandanunyah Formation (ᵽUy-sl)

The Yandanunyah Formation (*ᵽUy*; Williams, 1989) outcrops in the southwestern part of LAMIL, where it conformably overlies the Brownrigg Sandstone. The formation is about 300 m thick and consists of interbedded purple, red, yellow, and white siltstone and shale, commonly silicified calcareous shale, and rare silicified, blue-white oolitic and laminated dolomite that is stromatolitic in places (*ᵽUy-sl*). Williams and Trendall (1998) suggested that the formation, like the Waroongunyah Formation, is a transgressive shallow-marine sequence probably deposited shorewards of carbonate build-ups.

Yeneena Basin

Williams (1990a) defined the 'Yeneena Basin' to include three geographically separated packages of fluvial–marine sedimentary rocks. These packages were later given 'group' status and, from east to west, were named the Tarcunyah, 'Throssell' (now Throssell Range; Grey et al., 2005), and Lamil Groups (Bagas et al., 1995; Williams and Bagas, 1999). The Tarcunyah Group was subsequently allocated to the northwest Officer Basin (Bagas et al., 1995, 1999), and the definition of the Yeneena Basin was modified to include only the Throssell Range and Lamil Groups (Fig. 4; Grey et al., 2005).

The precise ages of the Lamil and Throssell Range Groups are uncertain. Chin and de Laeter (1981) suggested that the Throssell Range Group (then called the 'Yeneena Group') was deformed at 1132 ± 21 Ma. This deformation event has since been termed the Miles Orogeny (Bagas and

Smithies, 1998), and is now thought to be c. 720 Ma in age (Bagas et al., 2002).

Provenance studies using U–Pb SHRIMP ages for detrital zircons by Bagas et al. (2002) suggest that both groups are correlatives, and can be included in the Centralian Superbasin of Walter et al. (1995). The detrital zircon ages also show that both groups are younger than c. 1070 Ma (Bagas et al., 2002). Furthermore, samples of galena from the Holly and Warrabarty prospects in the Broadhurst Formation on BRAESIDE have imprecise $^{207}Pb/^{206}Pb$ model ages of between 940 and 760 Ma (Western Mining Corporation Ltd, unpublished date quoted by Williams and Trendall, 1998). It is also known that the Lamil Group is older than c. 654 Ma, which is the SHRIMP U–Pb titanite age for the Mount Crofton Granite (Dunphy and McNaughton, 1998). These data suggest that the Throssell Range and Lamil Groups are Neoproterozoic in age.

Throssell Range Group

The Throssell Range Group (Williams and Bagas, 1999) outcrops in the western part of LAMIL, where it consists of the basal siliciclastic Coolbro Sandstone, and overlying Broadhurst Formation. Cainozoic sediments conceal the contact between these formations on LAMIL, but it is conformable on BROADHURST to the southeast where outcrop is good (Hickman and Clarke, 1994).

The geological complexity of the area is difficult to document because rock exposures are limited, stratigraphic relationships between rock types are generally poorly established, outcrops are deeply weathered, and the rocks are typically covered to significant depths by recent gravelly, iron-pisolitic sand or clay and Carboniferous–Permian glacial deposits (which are widespread on LAMIL). For example, the sandstone forming the Throssell Range to the south of the Nifty deposit is assumed to be the Coolbro Sandstone, which on BROADHURST to the southeast is stratigraphically situated below the Broadhurst Formation. However, the relationship between the sandstone south of Nifty and the Broadhurst Formation is not established on LAMIL, and hence its identification as the Coolbro Sandstone on LAMIL remains tentative.

Coolbro Sandstone (ꝐTc-stq)

Sandstone that is correlated with the Coolbro Sandstone (*ꝐTc*; Williams et al., 1976) and exposed in the Throssell Range on southwestern LAMIL is interbedded with poorly exposed siltstone and shale. The thickness of the formation cannot be determined on LAMIL due to complex folding, and neither the top nor bottom of the formation is exposed. On BROADHURST to the southeast, the formation ranges in thickness between 2 and 4 km (Hickman and Clarke, 1994).

The Coolbro Sandstone comprises fine- to coarse-grained, and massive to well-bedded quartz sandstone, with minor siltstone and shale (*ꝐTc-stq*). Individual beds, where they are recognized, are commonly less than 5 m thick. The sandstone consists of recrystallized quartz grains with interstitial sericite, accessory tourmaline, and rare zircon grains. Siltstone and shale interbeds are poorly exposed (or recessive) units that are commonly sheared due to their incompetent nature and flexural-slip movement between massive sandstone units during folding, and are commonly veined by quartz. Rarely preserved cross-lamination and ripple marks (Fig. 9) indicate that palaeocurrents were towards the north and northeast prior to folding, which is consistent with the general trend of palaeocurrents in the formation on THROSSELL (Williams and Bagas, 1999) and BROADHURST (Hickman and Clarke, 1994).

Broadhurst Formation (ꝐTb-slh, ꝐTb-kd)

The Broadhurst Formation (*ꝐTb*; Williams et al., 1976) conformably overlies the Coolbro Sandstone on BROADHURST and RUDALL where the formation is best exposed (Hickman and Clarke, 1994; Hickman and Bagas, 1998). The thickness of the formation cannot be estimated on LAMIL because of poor exposure, complex folding, and faulting. On BROADHURST, the formation is approximately 2 km thick (Hickman and Clarke, 1994).

The Broadhurst Formation on LAMIL outcrops around the Nifty mine and Goosewhacker copper prospect. The formation in both areas consists of carbonaceous shale and siltstone, with thin interbedded siltstone, shale, and fine-grained sandstone (*ꝐTb-slh*). The carbonaceous shale and siltstone are commonly dark grey to black in colour, dolomitic, and thinly laminated. The shale is locally chloritic, thinly laminated, and occasionally has millimetre-scale ?barite casts. The siltstone is micaceous and chloritic, and is interbedded with laminated shale containing ?barite casts. These rocks locally contain cubic and disseminated pyrite and pyrrhotite crystals, constituting about 10% of the rocks. The pyrite also forms trains of medium-grained clots and blebs that are parallel to bedding. The pyrrhotite gives the formation a distinctive aeromagnetic signature across LAMIL. Concealed dolarenite interbedded with dolomite, siltstone, and shale (*ꝐTb-kd*) has been intersected in RAB drillholes to the east of Nifty (Birla Minerals Pty Ltd, unpublished data).

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Figure 9. Medium-grained sandstone with ripple marks from the Coolbro Sandstone (MGA 368580E 7567050N)

The exposed sections of the Broadhurst Formation on LAMIL are probably some hundreds of metres above the bottom of the formation. This suggestion is based on the presence of similar sandstone beds and a similar magnetic signature of the lower part of the formation on BROADHURST and RUDALL (Hickman and Clarke, 1994; Hickman and Bagas, 1998).

Lamil Group

The Lamil Group (Williams and Bagas, 1999) is a sandstone–shale–carbonate (limestone and dolomite) succession comprising the Malu, Puntapunta, and Wilki Formations (Fig. 4), which outcrops in northeastern LAMIL.

Turner (1982) proposed an intracratonic basin setting for the deposition of the Lamil Group and suggested that deposition took place at a continental margin or within a failed rift. Harris (1985, 1987) suggested that the group was deposited in a pull-apart basin developed in an extensional strike-slip system. This model is similar to that proposed for the Throssell Range Group on RUDALL (Hickman and Bagas, 1995, 1999).

The deformation history of the Lamil Group includes northeasterly directed compression and upright folding with associated faulting. Bagas (2000) assigned the main deformation event to the Miles Orogeny of Bagas et al. (1995), and suggested that it commenced early in the history of the group, probably during diagenesis.

Malu Formation (ⱣLm-stq, ⱣLm-ss)

The Malu Formation (*ⱣLm-stq*; Bagas, 2000) includes the Telfer Member (*ⱣLm-ss*) at its top. Both units contain quartz-rich sandstone, siltstone, and shale, although the Telfer Member contains a higher proportion of siltstone, and rare dolomite near its top. The Malu Formation is at least 2 km thick at the Malu Hills and at depth in the Telfer mine on PATERSON (Bagas, 2000).

Turner (1982) interpreted the Malu Formation as deep-water turbidite deposits in northeasterly prograding submarine fans, and inferred that the Telfer Member represents a transition from deep water to an outer carbonate-shelf environment (represented by the overlying Puntapunta Formation).

Telfer Member (ⱣLm-ss)

The Telfer Member (*ⱣLm-ss*; Bagas, 2000) is a transitional sequence at the top of the Malu Formation (*ⱣLm-stq*) and below the Puntapunta Formation. The base of the member is at the top of the massively bedded sandstone in the underlying part of the Malu Formation, and the top is at the uppermost sandstone bed (Bagas, 2000). The member is about 600 m thick.

The Telfer Member consists of fine- to medium-grained quartz sandstone interbedded with clayey sandstone, siltstone, and shale. The sandstone beds are typically well sorted, very fine to fine grained, and consist of quartz, plagioclase, sericite, and minor authigenic dolomite. Sedimentary structures are rarely preserved due to recent widespread silicification of the region (Bagas, 2000). Siltstone beds are laminated and commonly spotted with authigenic dolomite grains. The siltstone consists of quartz, carbonate, plagioclase, sericite, tourmaline, zircon, and sulfides (mostly pyrite).

Puntapunta Formation (ⱣLp-kd)

The Puntapunta Formation (*ⱣLp*; Chin et al., 1982) is a laminated to thinly bedded sequence of dolarenite interbedded with dolomite, siltstone, and shale (*ⱣLp-kd*). The formation conformably overlies the Malu Formation, and is conformably overlain by the Wilki Formation (Fig. 4; Bagas, 2000). The Puntapunta Formation is poorly exposed on LAMIL. The formation outcrops to the south of the Mount Crofton Granite where it includes hornfelsed, yellow, pink, and brown, thinly bedded, and fine- to medium-grained dolomite interbedded with siltstone. The formation is about 1.5 km thick in the northwestern part of PATERSON (Bagas, 2000).

Wilki Formation (ⱣLw-stq)

The Wilki Formation (*ⱣLw*; Wilki Quartzite of Chin et al., 1982) is the youngest exposed stratigraphic unit of the Lamil Group on LAMIL. The formation is about 1.4 km thick and appears to conformably overlie the Puntapunta Formation (Bagas, 2000), although the contact between the two formations is not exposed. Much of the Wilki Formation is a monotonous sequence of silicified fine- to medium-grained sandstone, and minor recessive shale and laminated sandstone (*ⱣLw-stq*). The sandstone is moderately sorted, quartz-rich, with subrounded to well-rounded quartz grains in a matrix of quartz and sericite. Hornfelsed sandstone north of the Mount Crofton Granite contains recrystallized and interlocking quartz grains with minor chlorite, muscovite, and tourmaline. Sedimentary structures are rarely preserved in this formation.

A shallow-marine environment is tentatively inferred for the Wilki Formation (Turner, 1982).

Structures associated with the Miles Orogeny

The Miles Orogeny (D_{3-4}; Bagas and Smithies, 1998; Bagas, 2004b) is the first Neoproterozoic orogenic event in the northwestern Paterson Orogen. It produced northwesterly trending folds and faults in the Tarcunyah, Throssell Range, and Lamil Groups, and locally developed D_3 thrusts and recumbent F_3 folds in the Throssell Range Group to the southeast on BROADHURST, and RUDALL (cf. Hickman and Clarke, 1994; Bagas and Smithies, 1998). F_3 fold axes, and associated S_3 axial-planar cleavage to the southeast, trend about 120° and are overprinted by D_4 structures (folds, crenulation cleavage, and faults; Bagas and Smithies, 1998). No distinct metamorphic event (M_3) associated with D_3 has yet been identified. The orogeny is possibly coincident with the c. 750–720 Ma Areyonga tectonic movement affecting the lower Neoproterozoic part of the Amadeus Basin in central Australia and the Officer Basin in Western Australia (Moors and Apak, 2002).

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Figure 10. Disharmonic F_4 folds in medium-grained sandstone from the Coolbro Sandstone. The fold in the photograph plunges 30° to the north (MGA 349200E 7593550N)

Structures associated with the Miles Orogeny on LAMIL are best seen in the Coolbro Sandstone (Fig. 10), Malu Formation, and Wilki Formation. Structures include: kilometre-wide, regional, doubly plunging disharmonic folds with northwesterly trending axes and associated S_4 axial-planar cleavage; a conjugate set of oblique faults trending north-northeast and east-southeast with a component of either dextral or sinistral strike-slip movement respectively; and rare recumbent folds derived from bedding-parallel slip during the regional D_4 folding. The recumbent folds probably correlate with structures associated with the D_3 event observed elsewhere (e.g. Hickman and Clarke, 1994). Thinning of limbs and thickening of hinges are common in F_4 folds, and the S_4 foliation is frequently faulted. The north-northwesterly trending, doubly plunging, upright folds in the Tarcunyah Group are most probably D_4 structures that have been faulted by the reactivated Vines Fault during D_6.

The general orientation of D_3 and D_4 structures indicates a northeasterly to southwesterly orientated shortening regime. Both deformations have been interpreted as progressive events during the Miles Orogeny (Bagas and Smithies, 1998).

Soft-sediment deformation is common in the Lamil Group suggesting that the Miles Orogeny was probably active in the area during the early history of the group (Bagas, 2000). The youngest age of c. 1070 Ma, obtained from the presence of major detrital zircon populations of that age from samples of sandstone from the Lamil Group on PATERSON, and from the Throssell Range Group on BROADHURST and RUDALL, provides a maximum age for both groups (see Bagas et al., 2002). This also shows that the Miles Orogeny must have taken place after c. 1070 Ma. The minimum age for the orogeny is c. 654 Ma, which is the maximum titanite SHRIMP U–Pb age of granites post-dating D_4 structures in the Lamil Group (Dunphy and McNaughton, 1998).

Regional metamorphism

The Miles Orogeny is characterized by low-grade regional metamorphism on LAMIL. The lower- or sub-greenschist facies mineral assemblage in the Throssell Range and Lamil Groups consists of quartz, albite, sericite, hematite, epidote, dolomite, chlorite, and rare stilpnomelane. Even though the grade of metamorphism in the Tarcunyah Group to the west is lower, no conclusion can be made about its age relative to the Throssell Range and Lamil Groups. As mentioned earlier, the contact between the Tarcunyah and Throssell Range Groups is a major fault system represented by the Vines–Southwest–McKay fault system (Fig. 1).

Granitic rocks

The Lamil Group is metamorphosed and intruded by granite near Mount Crofton on northeastern LAMIL (Fig. 11). Outcropping granitic rocks range in composition from monzogranite to syenogranite, and are usually massive and not deformed. They are highly fractionated (with average SiO_2 contents >71 wt% and Rb/Sr ratios up to 20.5), metaluminous, and I-type in nature (Goellnicht et al., 1991; Goellnicht, 1992). The development of contact metamorphic aureoles is variable and difficult to recognize due to the silica-rich sandstone units that the granite intrudes. The aureoles are up to 2 km wide, reach the pyroxene-hornfels facies grade (Chin et al., 1982), and contain veinlets of quartz and biotite; cordierite porphyroblasts are present in pelitic rocks.

Mount Crofton Granite (Ꝑcr-grl, Ꝑcr-gm)

The Mount Crofton Granite (*Ꝑcr-g*; Chin et al., 1982) is well exposed in several prominent hills in the northeastern corner of LAMIL. Minor dykes of aplite and pegmatite (with chilled aplitic margins) intrude the granite. The pegmatite contains quartz, biotite, and muscovite. The

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Figure 11. Dykes of fine-grained monzogranite with chilled margins, and thin hornfelsed contact zones in the Wilki Formation (MGA 391800E 7615900N)

granite is predominantly medium- to coarse-grained biotite monzogranite (*Ꞓcr-gm*), and medium-grained, equigranular leucocratic syenogranite (*Ꞓcr-grl*). The monzogranite grades into porphyritic phases that are considered local variants. The monzogranite consists of perthitic K-feldspar (orthoclase and minor microcline), which is megacrystic in places, quartz, minor biotite, plagioclase with myrmekitic rimming, apatite, titanite, zircon, allanite, opaque minerals, and rare hornblende. The syenogranite consists of perthitic K-feldspar, lesser amounts of zoned plagioclase, minor biotite, titanite, zircon, apatite, and opaque minerals.

Two samples from the Mount Crofton Granite have titanite SHRIMP U–Pb ages of 640 ± 8 and 654 ± 8 Ma (Dunphy and McNaughton, 1998). These ages are regarded as the most valid for constraining the true crystallization age of the samples, given the high to extremely high concentration of uranium in the zircons that has essentially destroyed their structure and resulted in significant lead loss (Dunphy and McNaughton, 1998). The zircon ages for the same samples range from c. 630 to 600 Ma (Nelson 1995, 1999), and are therefore minimum ages for the granitic rocks and not their crystallization ages (Dunphy and McNaughton, 1998).

Structures related to intrusion of the Mount Crofton Granite

The Wilki Formation forms broad, steeply dipping synformal structures around the western edge of the poorly exposed Mount Crofton Granite on LAMIL. Geophysical data suggest that these granite bodies are thin laccolithic sheets with subhorizontal tops (Dimo, 1990).

Bagas (2000) proposed that these structures are related to the emplacement of the laccolithic granites, which caused doming of overlying rocks and down-folding of rocks adjacent to the stem margins of the granitic intrusion. In this model, down-folding and bedding-plane slip would play important roles in the evolution of such structures.

Quartz veins and dolerite dykes (*zq*, *od*)

Quartz veins (*zq*) are commonly located in faults and shear zones, and are assumed to be Neoproterozoic in age. Some veins are limonitic, particularly along their margins, and indicate wallrock sulfidation reactions. Other quartz veins contain limonite and goethite in late fractures. A series of easterly trending quartz veins at the Goosewhacker prospect on southern LAMIL vary up to 0.2 m in width and up to 120 m in length. The veins are subparallel to bedding and contain carbonate (siderite), sulfides, and rare galena, chalcopyrite, and sphalerite. The veins are anomalous in lead, copper, arsenic, and silver (Chin et al., 1982).

Poorly exposed, north- to northeast-trending dolerite dykes (*od*) interpreted from aeromagnetic data, crosscut faults that affect the Throssell Range Group, thereby indicating that the dykes are relatively young. Hornfelsed dolerite, observed in diamond drillcore from hornfels zones around Mount Crofton Granite and in the Malu Hills area on PATERSON (Bagas, 2000), suggests that the dolerite was intruded before, or synchronously with, the Mount Crofton Granite.

Structures associated with the Paterson Orogeny

The last major Proterozoic event recorded on LAMIL was the c. 550 Ma Paterson Orogeny (D_6), which reactivated earlier structures (Hickman and Bagas, 1998), and post-dates deposition of c. 610 Ma glacigene rocks of the Boondawari Formation of the northwest Officer Basin (Williams, 1992; Williams and Tyler, 1991). This event is probably equivalent to the c. 550 Ma Petermann Orogeny (Camacho and Fanning, 1995) of the Musgrave Complex in central Australia, and synchronous with the King Leopold Orogeny of the Kimberley region of northern Western Australia (Shaw et al., 1992). Regional gravity data indicate that structures associated with the Petermann Orogeny extend to the northwest into the Paterson Orogen, and these structures coincide with the edges of the Anketell Gravity Ridge (Fraser, 1976). These Neoproterozoic orogenies were active during a period of global plate reorganization, commonly known as the Pan-African event, involving the initiation of subduction and convergent plate-margin activity during the assembly of Gondwana (Cawood and Leitch, 2001).

Structures associated with D_6 consist of northerly to northwesterly striking dextral faults, east-northeasterly striking sinistral faults, and the associated strain-slip cleavage (S_6). These are near-vertical conjugate strike-slip faults that indicate south-southwest-directed shortening (Fig. 6).

The concealed Vines Fault in southwestern LAMIL is interpreted to be a dextral transpressional fault associated with the Paterson Orogeny (Williams and Trendall, 1998). The structure appears to truncate F_4 folds in the Coolbro Sandstone on LAMIL.

A late, brittle (regional D_7) deformation event has been recognized in the Throssell Range, which has not been documented elsewhere in the northwestern Paterson Orogen. Structures associated with this event are northeasterly trending dextral faults with a normal component of movement, and normal reactivation of northwesterly trending faults forming a graben structure recognized in seismic surveys in the Waukarlycarly Embayment (Fig. 12). This event is younger than c. 550 Ma and older than, or synchronous with, the deposition of Devonian to Permian sedimentary rocks in the Canning Basin. This is deduced from petroleum exploration drilling in Permian rocks on CARDOMA in the Wallal Embayment to the northwest, and in Devonian (or older) and Permian rocks on LARSEN in the Anketell Shelf to the east (D'Ercole et al., 2003; D'Ercole and Ghori, in prep.). This deformation event is probably connected with the Pillara Extension recognized in the northeastern part of the Canning Basin (Kennard et al., 1994), which includes major extension, rifting and subsidence, or it could be the

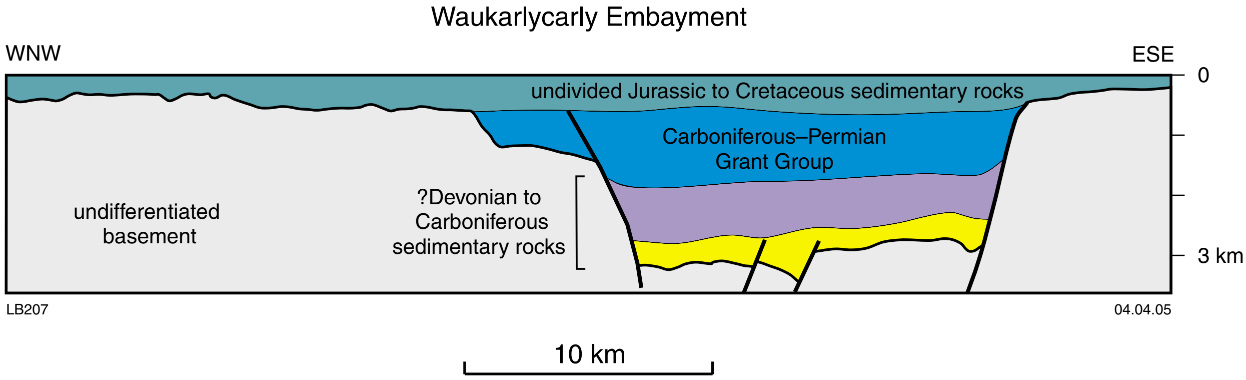

Figure 12. Interpreted seismic section over the Waukarlycarly Embayment north of LAMIL. The inferred stratigraphic succession is based on D'Ercole and Ghori (in prep.). The section is based on an interpretation of seismic line H96-01 using seismic data collected along the Telfer Road in 1996 (Hunt Oil Company, 1996). The location of the seismic line is shown in Figure 1

first evidence in the Paterson Orogen for the widespread and complex Alice Springs Orogeny (400–300 Ma).

Canning Basin

Carboniferous–Permian fluvioglacial deposits of the Paterson Formation in the Canning Basin cover the poorly exposed Waukarlycarly Embayment in central LAMIL (Fig. 5). Few conclusions can be drawn about the nature of the embayment apart from the interpretation of seismic data collected along the Telfer Road on BRAESIDE, WAUKARLYCARLY, and northeastern LAMIL (Fig. 1), which indicates that the embayment includes a graben-like structure that contains at least 3 km of Phanerozoic sedimentary rocks (Fig. 12).

Carboniferous–Permian rocks

The distribution of Carboniferous–Permian rocks is shown in Figure 5. These rocks form part of the Canning Basin succession.

Paterson Formation (CPpa)

The Paterson Formation (*CPpa*; Traves et al., 1956) is located in the eastern, central, and southwestern parts of LAMIL. It appears to have been deposited in a palaeoglacial valley that developed on Proterozoic rocks. The Paterson Formation contains fluvioglacial and diamictite deposits that comprise boulder to pebble conglomerate, cross-bedded and coarse-grained sandstone, and mudstone (*CPpa-sgpg*).

Cainozoic deposits

Cainozoic deposits on LAMIL are dissected and variably cemented sediments that mantle Proterozoic rocks. Areas of active sedimentation are mapped as Quaternary deposits. Individual Cainozoic and Quaternary units have been mapped from aerial photograph interpretation and limited field observations.

Residual or relict units (Rf, Rk, Rz)

Gently undulating duricrust surfaces, which include ferricrete or ironstone deposits (*Rf*) and silcrete deposits (*Rz*), contain areas of exposed bedrock. The ferricrete grades downward into leached and kaolinized, deeply weathered rock. Silcretes are probably early Cainozoic or older in age and may represent a continent-wide weathering event (Idnurm and Senior, 1978), or are silicified and leached zones developed at the base of Carboniferous–Permian rocks. Calcrete (*Rk*), consisting of massive, vuggy, or nodular sandy limestone with local opaline caprock, is a few metres thick and present in drainage channels in the eastern parts of LAMIL. Longitudinal sand dunes transgress and overlie calcrete.

Colluvial deposits (C2)

Dissected and variably cemented colluvium, sheetwash, alluvial fan deposits, and talus (*C2*), are composed of boulders, gravel, sand, and silt. These units are derived from various rock types, but are mainly from those rock types that are relatively resistant to weathering and erosion and form the adjacent hilly areas.

Quaternary deposits

Lacustrine units (L_p, L_m)

Playa lake deposits (L_p) consist of clay, silt, and evaporites. The unit is found in low-lying areas marginal to drainage channels, or at the termination of creeks against sand dunes. Lake sediment comprises a mixture of black to brown mud, evaporite, and sand. Seasonal grasses and scattered eucalypts are the only types of vegetation on the lake surface. Mixed lacustrine and eolian deposits that cannot be divided are labelled as 'L_m'.

Alluvial deposits (A)

Poorly developed drainage courses and associated floodplains contain alluvium (*A*), which consists of unconsolidated clay, silt, sand, and gravel. The floodplain deposits also contain sand and clay mixed with eolian sand.

Eolian units (E, Ef)

Flat to undulating eolian sandplains and variably spaced longitudinal (seif) dunes (*E*), cover large parts of LAMIL. The sandplains and seif dunes consist of dark-red eolian sand, and clayey sand. The sand comprises iron-stained quartz grains that have diameters of up to 0.5 mm mixed with minor amounts of ferricrete grains and pebbles. The dunes are up to 30 m in height, many kilometres long, and have a westerly to northwesterly orientation that parallels the prevailing wind direction. Sand movement is confined to the dune crests, and a cover of spinifex (*Triodia* sp.) and small eucalypt bushes stabilizes their sides. Some dunes terminate on the eastern side of outcrops or where drainage channels cut them. The depth of the sand between dunes is commonly less than 2–3 m, as revealed by exposed pediments and an absence of trees. The sand unit (*Ef*) is common throughout LAMIL, and is a mixture of residual and transported ferricrete granules, pebbles, and eolian sand. There is a lithological gradation between *E* and *Ef*, and distinguishing between these two units is difficult in places.

Second generation colluvial and alluvial units (C1, Wf)

Poorly developed red-earth soils, consisting of ferruginous lag gravel or gibber, contain ferricrete rubble, clay, silt, and sand (*Wf*). This unit is developed in poorly drained areas. Gently sloping scree and outwash fans alongside ridges and hills are composed of colluvial sand, soil, and gravel (*C1*). Extensive colluvial fans locally grade into alluvium downstream.

Economic geology

Mineral exploration on LAMIL was extremely limited until 1971 when the Telfer gold deposit was discovered on PATERSON. This stimulated interest in the region and many mineral exploration companies subsequently explored the map area in search of gold, which lead to the discovery of the Lamil Hills South (also known as Anomaly 1; 10449*), North Magnetic (10597), Egg (10450), and Stuttgart (13042) gold prospects in the northeastern part of LAMIL (Stewart, 1998).

Based on a conceptual model, WMC searched for sediment-hosted Zambian-style copper mineralization in the Throssell Range Group during 1980, and following reconnaissance geochemical surveys, discovered the Nifty (Cu–Pb–Zn; 10038) deposit in 1981 (Haynes et al., 1993). Subsequent exploration led to the discovery of the Nifty Southeast (Cu; 10545), Nifty Finch (Cu; 10544), Finch (Cu–Pb–Ag; 10542), Finch East (Pb–Zn; 10543), and Citadel (Zn–Pb; 10541) prospects on LAMIL.

Exploration company data covering LAMIL are held in the Western Australia Mineral Exploration Index (WAMEX) open-file system at the GSWA library.

Gold

Exploration in the Lamil Hills area of LAMIL included: rockchip, deflation lag, and stream sediment sampling; ground magnetic, aeromagnetic, aeroradiometric, and gravity surveying; and rotary air blast, reverse circulation, and diamond drilling (Stewart, 1998). This work delineated the Lamil Hills South (10499), Egg (10450), North Magnetic (10597), and Stuttgart (13042) prospects (Stewart, 1998). These gold occurrences may be similar in age to the Telfer deposit, but information on the absolute age of the gold mineralization in the region is not available.

The Lamil Hills South and Egg prospects are hosted by fine-grained quartz sandstone in the Telfer Member of the Malu Formation. The mineralization is gossanous and fracture controlled, and consists of disseminated limonite (after pyrite) that is anomalous in Au–Cu–Zn–As (Stewart, 1998). Both prospects consist of gossanous quartz-veins containing limonite–goethite–pyrite–chalcopyrite–pyrrhotite–arsenopyrite in stockwork or breccia. Diamond drilling at Lamil Hills South returned a result of 21.7 g/t Au associated with elevated arsenic concentrations over 0.2 m, and a 6 m-long diamond-drillhole sample of gossan from the Egg prospect returned 1.32 g/t Au (Stewart, 1998).

Newcrest Mining Limited assigns carbonate rocks that host the North Magnetic prospect to the Puntapunta Formation. The mineralization consists of thin auriferous stockworks of quartz–pyrite–carbonate veins. A 0.8 m-wide diamond-drillhole sample assayed 6.49 g/t Au with elevated Ag–Cu–Pb–Zn (Stewart, 1998).

The Stuttgart prospect is sited over a stockwork of quartz with limonite after sulfide veining, and disseminated sulfides in northeast-trending fractures. The stockwork is about 3 m wide and assays up to 3.82 g/t Au, 560 ppm Cu, and 0.15% As (Stewart, 1998).

Skarn

Anomaly 2 (MGA 391900E 7609400N) and 3 (MGA 392250E 7608500N), delineated by Newcrest Mining Limited in the Lamil Hills area, are non-auriferous skarn deposits composed of disseminated pyrrhotite–pyrite(–chalcopyrite–scheelite) in calcarenite of the Telfer Member in the Malu Formation (Stewart, 1998).

Copper, lead, zinc, silver

Nifty Cu–Pb–Zn deposit

The Nifty Cu–Pb–Zn deposit is a stratabound epigenetic deposit hosted by carbonate rocks and shale of the Broadhurst Formation (Throssell Range Group). Copper

* Western Australia Mineral Occurrence database (WAMIN) reference numbers.

is the only metal recovered from the deposit, but minor sphalerite, galena, and silver, and traces of gold and uranium minerals are present (Dare, 1994). The mine produced 25 103 t of cathode copper in 2003, and has a cumulative production of 151 467 t of cathode copper for the period between 1994 and 2003 (Department of Industry and Resources production records). At the end of 2001, Nifty had remaining oxide resources totalling 30.2 Mt at an average grade of 1.4% Cu, with 438 700 t of contained copper. Unworked sulfide resources total 109.7 Mt at an average grade of 1.3% Cu, with 146 400 t of contained copper (Straits Resources Ltd, 2002). A decline to access the sulfide ore was under construction in 2004.

There are three types of copper mineralization in the Nifty area: primary chalcopyrite; secondary, silicified carbonate-hosted copper; and secondary shale-hosted mineralization (Dare, 1994). The majority of the mineralization is structurally controlled in an F_4 syncline; this forms the primary style of mineralization and is confined to highly silicified and dolomitized rocks locally known as the 'pyrite marker bed' and the 'Nifty Member' (Dare, 1994). The mineralization includes chalcopyrite, pyrite, sphalerite, and galena (Dare, 1994), but most of the ore is disseminated to massive chalcopyrite (Dare, 1994). High-grade ore appears to be best developed in carbonate beds below shale beds, and there is a strong stratigraphic control (Dare, 1994).

Secondary mineralization is confined to shallow depths and is characterized by a vertical zonation from malachite–azurite passing downwards to malachite–cuprite–tenorite–native copper, and then down to a chalcocite-rich supergene zone (Dare, 1994). This type of ore also contains erratically anomalous gold (Dare, 1994). Current production is from the secondary (oxide) mineralization, which is mined as an opencut operation. The copper is extracted using heap leach, solvent extraction, and electrowinning techniques.

Remobilized mineralization is confined to a 15 m-thick zone that is between 40 and 80 m below the present water table and above the base of the oxidation front, and consists predominantly of malachite with minor amounts of azurite (Dare, 1994). This style of mineralization is interpreted by Dare (1994) to have formed by supergene enrichment or precipitation at the palaeowatertable.

The genesis of the Nifty copper deposit is related to deformation during the Miles Orogeny (Anderson et al., 2001). Hydrothermal fluids originating deep in the Yeneena Basin were focused along D_{Y2} thrust faults (Anderson et al., 2001). Chalcopyrite precipitation was controlled mainly by changes in pH accompanied by a slight decrease in temperature. The mineralization and alteration styles at Nifty are similar to those of the copper orebodies at Mount Isa (Anderson et al., 2001).

Nifty Southeast Cu prospect

The Nifty Southeast Cu prospect is located about 6 km to the southeast of the Nifty mine. Malachite was intersected at the prospect during a reconnaissance-drilling program by WMC in pyritic carbonaceous black shale of the Broadhurst Formation. However, subsequent drilling failed to intersect significant mineralization (WAMEX Item 6882: A30564, 34992).

Nifty Finch Cu prospect

The Nifty Finch area covers a continuous although concealed zone of conductive units that extend from north of the Nifty mine to north of the Finch prospect over a distance of about 30 km. The units in the zone consist of interbedded micaceous carbonaceous siltstone and shale, pyritic carbonaceous shale, thin carbonate units, and very fine grained sandstone of the Broadhurst Formation. A 2-m copper anomaly containing 0.44% Cu was delineated during reverse-circulation drilling at the Nifty Finch prospect, which is located about 7 km southeast of the Nifty deposit. Subsequent exploration failed to find any significant mineralization in the area (WAMEX Item 6882: A30564, 32976, 34992).

Finch Cu–Pb(–Ag) prospect

The Finch Cu–Pb(–Ag) prospect is located about 18 km southeast of the Nifty deposit mine. The prospect is located where the Nifty Syncline was interpreted by WMC to be truncated by a major fault beneath Cainozoic sediments below 40 to 120 m. Several percussion drillholes intersected native copper, malachite, anomalous lead, silver, and traces of gold at or above the oxidation zone, in shale and siltstone of the Broadhurst Formation (WAMEX Item 6882). The best drillhole intersections are 2 m thick assaying 1.5% Cu, and 24 m thick assaying 0.4% Pb (WAMEX Item 6882: A30564, A32976, A34992).

Finch East Pb–Zn prospect

The Finch East Pb–Zn prospect is located about 7 km east-southeast of the Finch prospect on a bullseye TEM conductor recognized by WMC. Narrow zones containing elevated levels of lead and zinc were intersected in a number of percussion drillholes in carbonaceous shale, siltstone, and fine-grained sandstone of the Broadhurst Formation (WAMEX Item 6882). The best drillhole intersections are 18 m at 0.3% Zn, and 2 m at 0.4% Pb and 0.35% Zn (WAMEX Item 6882: A30564, A34992).

Citadel Zn–Pb prospect

The Citadel Zn–Pb prospect is located about 10 km north-northeast of the Nifty mine in an area of no outcrop. The prospect area has patchy and elevated Cu and lesser Zn–Pb concentrations in pyritic and carbonaceous shale, siltstone, and minor dolomite and chert of the Broadhurst Formation. Two drillholes (THRC 116 and 128) yielded results ranging up to 12 m of 0.25% Zn and 14 m of 0.36% Zn about 120 m below surface (WAMEX Item 6882).

Goosewhacker Cu prospect

The Goosewhacker Cu prospect is located in the southeastern part of LAMIL, and consists of a series of easterly trending, gossanous stratiform quartz veins. The veins are hosted by northerly dipping and facing pyritic and carbonaceous shale and siltstone of the Broadhurst

Formation, and vary up to 0.2 m in width and 120 m in length. The veins contain native copper, malachite, carbonate (siderite), sericite, sulfides (pyrite, and minor chalcopyrite and arsenopyrite), and rare bornite, covellite, galena, hematite, marcasite, pyrrhotite, and sphalerite (Froud, 1997). The gossan is anomalous in lead, copper, arsenic, and silver (Chin et al., 1982).

Road material

Gravel pits and quarries for road material are found at irregular intervals along the main graded roads on LAMIL (Gvl 16939, 16940, 16941, 16942, 16943, 16944, 16945). Most material was obtained from unconsolidated Cainozoic gravel or lag deposits in eolian sands (*E*).

Hydrocarbon prospectivity

During the 1980s and 1990s petroleum exploration in the Canning Basin, including the acquisition of seismic data, yielded little commercial success (Kennard et al., 1994). Hunt Oil Company completed one of these seismic surveys in 1996 across an area known as the Waukarlycarly Embayment (Hunt Oil Company, 1996; Fig. 12). The embayment has potential for economic hydrocarbon accumulations but there is inadequate data to assess this potential.

Water resources

Areas of calcrete along palaeodrainage systems in the central and eastern part of LAMIL may contain large, although saline, groundwater supplies. Significant groundwater supplies are likely to be found in fractured and sheared sandstones of the Coolbro, Wilki, and Malu Formations, carbonate rocks in the Broadhurst Formation (e.g. around Nifty), and in the areas around major creek systems.

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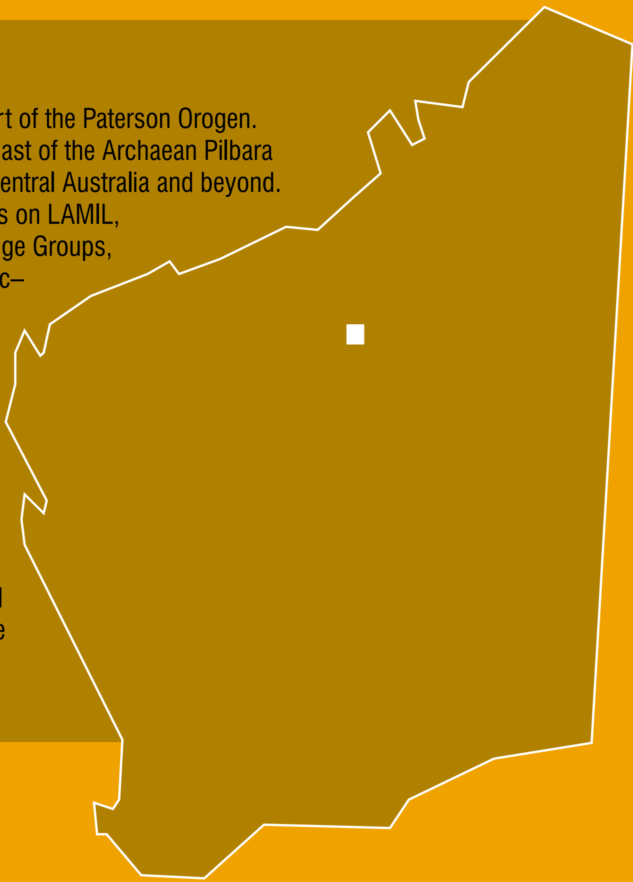
The LAMIL 1:100 000 sheet area is in the northwestern part of the Paterson Orogen. The orogen can be traced on regional gravity maps from east of the Archaean Pilbara Craton in Western Australia to the Musgrave Complex of central Australia and beyond. These Explanatory Notes describe the geology of the rocks on LAMIL, which include the Neoproterozoic Lamil and Throssell Range Groups, late Neoproterozoic granitic rocks, and Permian to Jurassic–Cretaceous rocks of the Canning Basin. The Lamil and Throssell Range Groups are younger than c. 1070 Ma and were deformed by the c. 720 Ma Miles Orogeny, which was probably associated with significant base metal mineralization in the Throssell Range Group. The Lamil Group was intruded at around 654 Ma by post-orogenic, I-type monzogranites and syenogranites that are broadly synchronous with major gold–copper mineralization. These Neoproterozoic rocks were deformed by the c. 550 Ma Paterson Orogeny. LAMIL is prospective for gold and base metals, and contains the Nifty mine, which is the only deposit being worked in the Throssell Range Group.



These Explanatory Notes are published in digital format (PDF) and are available online at: www.doir.wa.gov.au/gswa/onlinepublications. Laser-printed copies can be ordered from the Information Centre for the cost of printing and binding.

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BAGAS

Geology of the Lamil 1:100 000 sheet

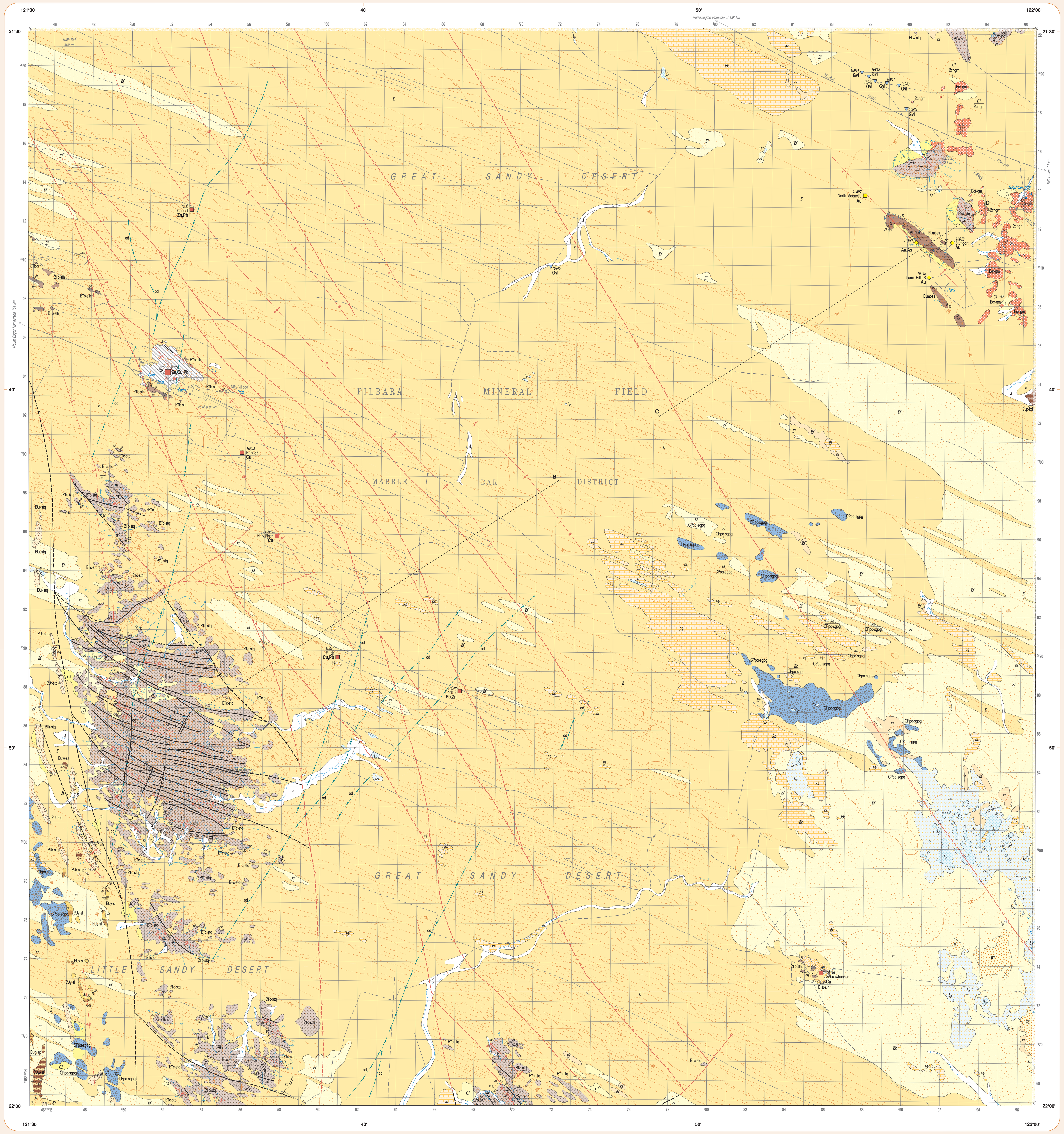
EXPLANATORY NOTES

AUSTRALIA 1:100 000 GEOLOGICAL SERIES

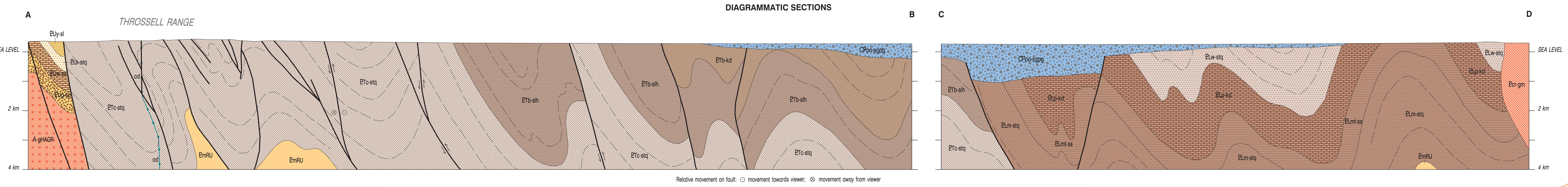
LAMIL

GEOLOGICAL SURVEY OF WESTERN AUSTRALIA

SHEET 3254



DIAGRAMMATIC SECTIONS



Reference

QUATERNARY

Colluvial and alluvial units, second generation
- C1 Locally derived sand and gravel; in scree and outwash-fan deposits
- W1 Ferruginous lag gravel or gibber plain; ferricrete rubble, clay, silt, and sand; in distal outwash deposits in poorly drained areas

Eolian units
- E Sand; includes sheets, and dunes with intervening sandy valleys containing local concentrations of ferricrete sand and pebbles
- Ef Ferricrete sand and pebbles, and sand

Alluvial unit
- A Silt, sand, and gravel in drainage channels and on floodplains

Lacustrine units
- Lp Clay and silt; non-vegetated claypan deposits
- Lm Mixed lacustrine and eolian deposits; clay, silt, and sand

Colluvial unit, first generation
- C2 Variably cemented outwash talus; dissected by present-day drainage

Residual or relict units
- Rf Ferruginous duricrust
- Rk Calcrete; massive, nodular, and cavernous sandy limestone; locally silicified
- Rz Siliceous caprock with angular quartz grains

PALAEOZOIC — CARBONIFEROUS–PERMIAN

CPpa-sgpg PATERSON FORMATION: sandstone, mudstone, conglomerate, and boulder conglomerate; tillite and other fluvioglacial deposits (CANNING BASIN)

- od Dolerite dyke; exposed, interpreted from aeromagnetic data
- zq Quartz vein

Paterson Orogeny (c. 550 Ma)

c. 654 Ma [1]

MOUNT CROFTON GRANITE
- Ecr-grl Leucocratic syenogranite; medium grained, equigranular
- Ecr-gm Biotite monzogranite; medium to coarse grained, equigranular to porphyritic

Miles Orogeny (c. 720 Ma)

PROTEROZOIC — NEOPROTEROZOIC

Throssell Range Group (<1070 Ma [2])
- ETb-kd Dolarenite interbedded with dolomite, siltstone, and shale (Section only)
- ETb-slh BROADHURST FORMATION: carbonaceous shale and siltstone, pyritic and pyrrhotitic shale, siltstone, and fine-grained sandstone
- ETc-stq COOLBRO SANDSTONE: massive to thick-bedded quartz sandstone; minor siltstone and shale

Lamil Group (<1070 Ma [2]) — YENEENA BASIN
- ELw-stq WILKI FORMATION: fine- to medium-grained quartz sandstone; massive to bedded; minor shale and laminated sandstone
- ELp-kd PUNTAPUNTA FORMATION: dominantly dolarenite interbedded with dolomite, siltstone, and shale; thinly bedded, fine to medium grained
- ELmt-ss Telfer Member: interbedded sandstone and shale; locally pyritic; minor carbonate rock
- ELm-stq MALU FORMATION: fine- to medium-grained quartz sandstone; minor interbedded shale and dolomite (Section only)

Tarcunyah Group (<1070 Ma [3]) — OFFICER BASIN
- EUy-sl YANDANUNYAH FORMATION: siltstone, shale, and fine-grained sandstone
- EUr-stq BROWNRIGG SANDSTONE: fine- to coarse-grained quartz sandstone; pyrite nodules
- EUw-ss WAROONGUNYAH FORMATION: shale, siltstone, sandstone, and dolomite
- EUg-sp GOOGHENAMA FORMATION: medium- to coarse-grained sandstone and pebble to boulder conglomerate

CENTRALIAN SUPERBASIN

PALAEOPROTEROZOIC – MESOPROTEROZOIC

2015–1222 Ma — EmRU Undivided meta-igneous and metasedimentary rocks (Section only) — RUDALL COMPLEX

ARCHAEAN

2763–2757 Ma [4 5] — A-gHAGR GREGORY GRANITIC COMPLEX: undivided granitoid rock (Section only) — PILBARA CRATON

MINERAL OCCURRENCES

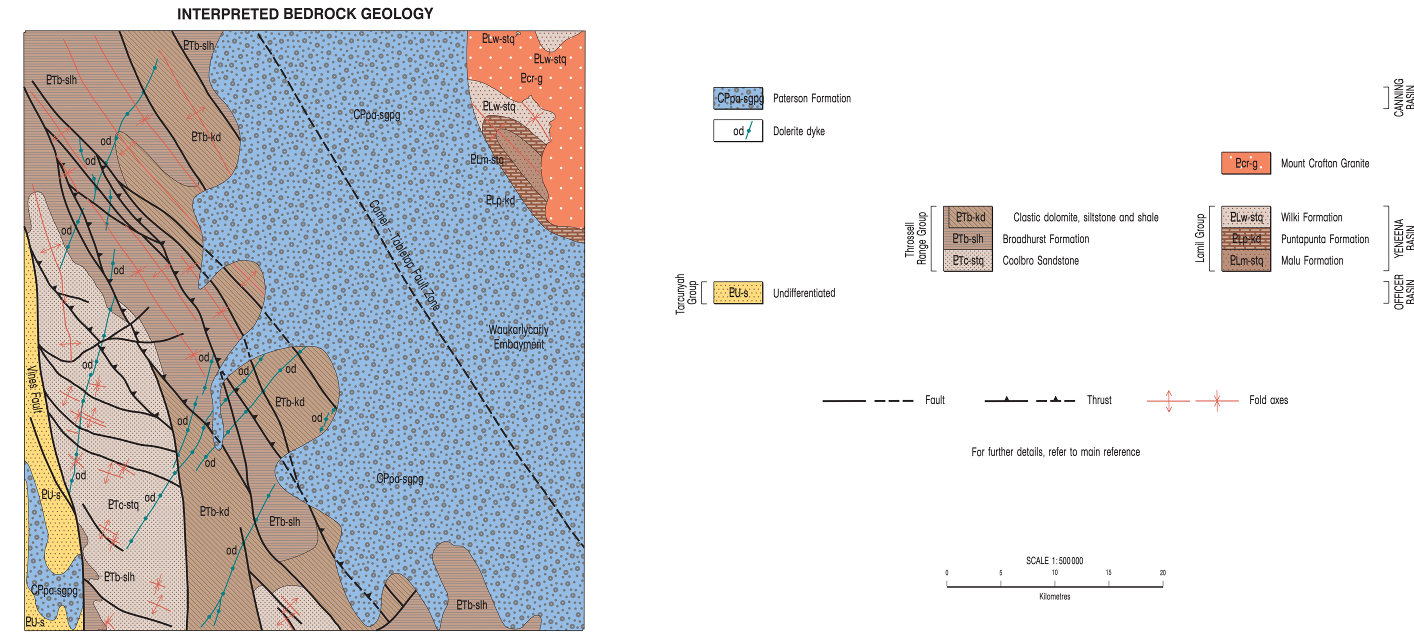
MINERALIZATION STYLES
- Vein and hydrothermal mineralization
- Stratabound sedimentary
- Undivided

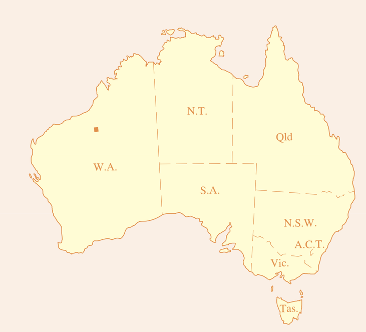
MINERAL AND ROCK COMMODITY GROUPS
- Precious metal
- Base metal
- Construction material

MINERAL AND ROCK COMMODITIES

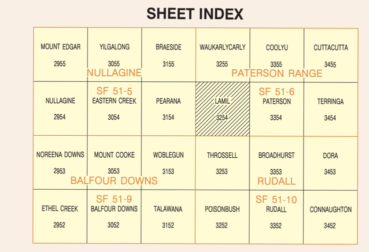
Arsenic	As
Copper	Cu
Gold	Au
Gravel	Gvl
Lead	Pb
Zinc	Zn

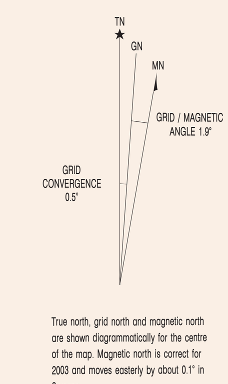
INTERPRETED BEDROCK GEOLOGY





SHEET INDEX





DATA DIRECTORY

Theme	Data Source	Data Currency	Agency
Geology	GSWA	2002	Dept of Industry and Resources
Structural data	WAROX	AUG 2002	Dept of Industry and Resources
Mineral occurrences	WAMIN	JUL 2003	Dept of Industry and Resources
Aeromagnetic data	Birla Minerals Pty Ltd	2004	Birla Minerals Pty Ltd
Cadastre	TENGRAPH	JUN 2002	Dept of Industry and Resources
Horizontal control	GESMAR	JUN 2002	Dept of Land Information
Topographic nomenclature	GEONOMA	JUN 2002	Dept of Land Information
Topography	DLI and GSWA field survey	2002	Dept of Land Information

Geology by L. Bagas 2002

Geochronology by:

(1) J. M. Dunphy and N. J. McNaughton, 1998, Geological Society of Australia, Abstracts, 49, p. 127.
(2) D. R. Nelson, 2002, GSWA Record 2002/2, GSWA sample 169117, 169119–20.
(3) D. R. Nelson, in prep., Compilation of geochronology data, October 2004 update GSWA sample 177102.
(4) D. R. Nelson, 1996, GSWA Record 1996/5, p. 143–152.
(5) D. R. Nelson, 1999, GSWA Record 1999/2, p. 94–96.

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Department of Industry and Resources

Geological Survey of Western Australia

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MINISTER FOR STATE DEVELOPMENT

JIM LIMERICK
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TIM GRIFFIN
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SCALE 1:100 000

UNIVERSAL TRANSVERSE MERCATOR PROJECTION
HORIZONTAL DATUM: GEOCENTRIC DATUM OF AUSTRALIA 1994
VERTICAL DATUM: AUSTRALIAN HEIGHT DATUM

Grid lines indicate 1000 metre interval of the Map Grid Australia Zone 51

The Map Grid Australia (MGA) is based on the Geocentric Datum of Australia 1994 (GDA94)
GDA94 positions are compatible within one metre of the datum WGS84 positions

Reference points to align maps based on the previous datum, AGD84, have been placed near the map corners

LAMIL

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