Department of
Industry and Resources

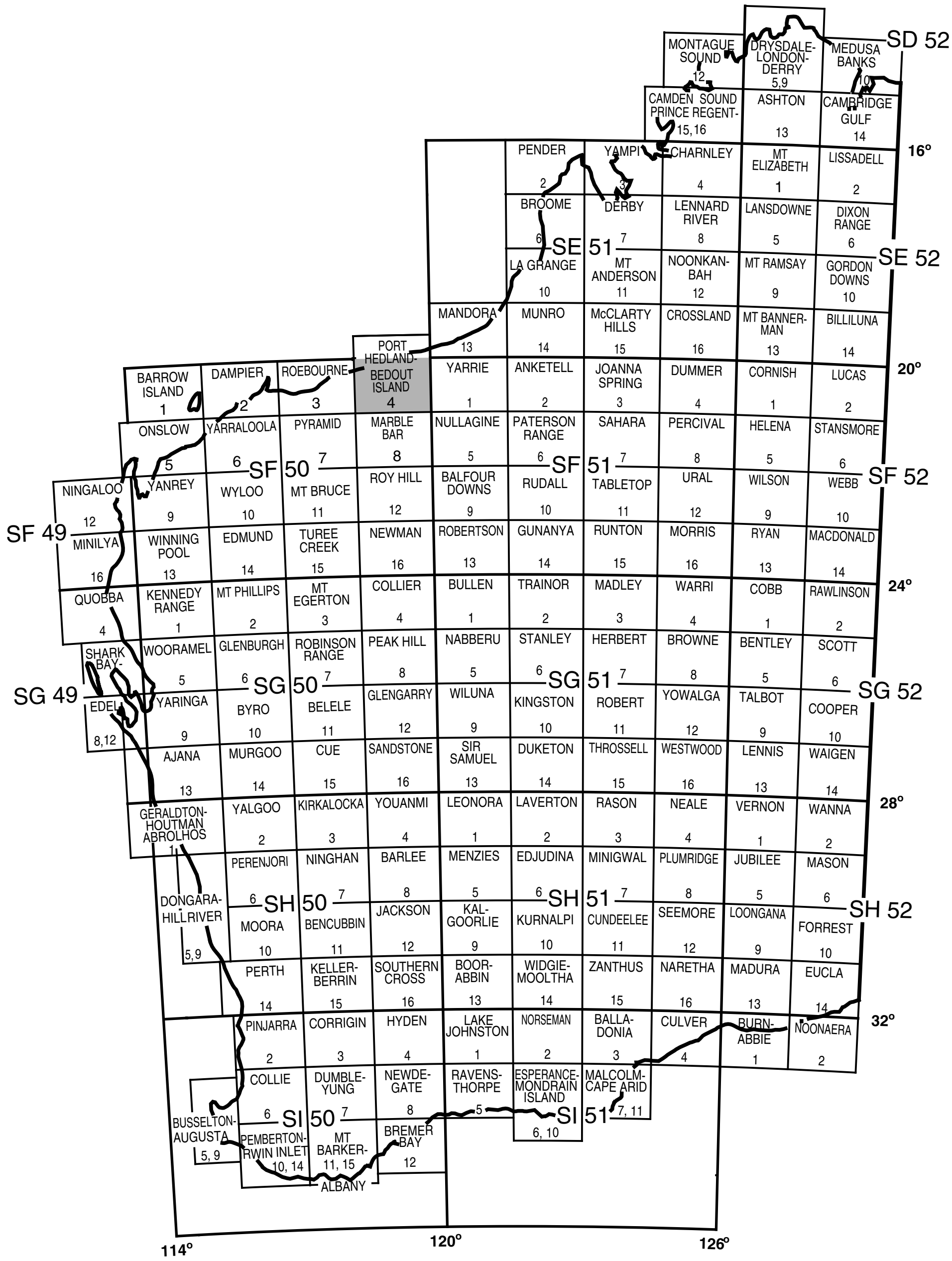
EXPLANATORY NOTES

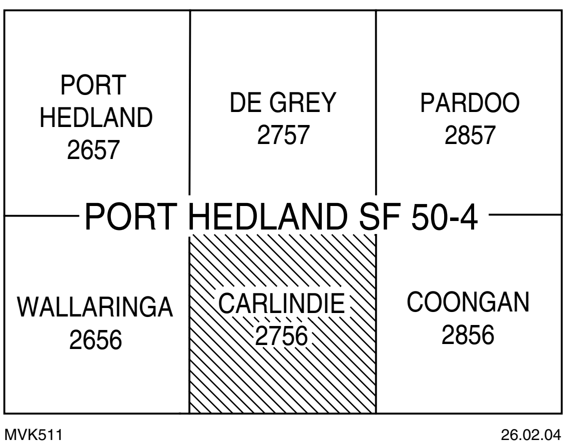
GEOLOGY OF THE CARLINDIE 1:100 000 SHEET

by M. J. Van Kranendonk

1:100 000 GEOLOGICAL SERIES

Geological Survey of Western Australia





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GEOLOGICAL SURVEY OF WESTERN AUSTRALIA

GEOLOGY OF THE CARLINDIE 1:100 000 SHEET

by
M. J. Van Kranendonk

Perth 2004

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Cover photograph:
Polymictic boulder conglomerate at the base of the Corboy Formation of the Gorge Creek Group (<c. 3235 Ma), which lies across an angular unconformity with the underlying, c. 3350–3325 Ma Euro Basalt of the Warrawoona Group (MGA $_{7}$55640E $_{76}$90200N).

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by

M. J. Van Kranendonk

Abstract

The CARLINDIE 1:100 000 sheet covers parts of the Palaeoarchaean to Mesoarchaean East Pilbara Granite–Greenstone Terrane of the northern part of the Pilbara Craton, and the Marble Bar Sub-basin of the Neoarchaean–Palaeoproterozoic Mount Bruce Supergroup. The East Pilbara Granite–Greenstone Terrane on CARLINDIE comprises greenstone successions of the Pilbara Supergroup and parts of the Carlindi and Pippingarra Granitoid Complexes. Volcano-sedimentary rocks belonging to five groups have been recognized, bound by angular unconformities and a basal intrusive contact with granitic rocks.

The Warralong greenstone belt in the southeast of CARLINDIE is composed of the c. 3515–3500 Ma Coonterunah Group, the Talga Talga, Salgash, and Kelly Subgroups of the c. 3490–3310 Ma Warrawoona Group, the c. 3255–3235 Ma Sulphur Springs Group, and the undated rocks of the <3235 to 2940 Ma Gorge Creek Group. Barite deposits in the core of the Warralong Syncline are ascribed to hydrothermal-fluid circulation during emplacement of the Sulphur Springs Group. A small part of the Panorama greenstone belt in the far southeast of CARLINDIE contains the Euro Basalt (Kelly Subgroup of the Warrawoona Group) and the Gorge Creek Group. The Warralong and Panorama greenstone belts are separated by the c. 2940 Ma Lalla Rookh Sandstone of the De Grey Group that is preserved within the fault- and unconformity-bound Lalla Rookh Synclinorium. Highly metamorphosed and strongly deformed relicts of the Cleaverville Formation (Gorge Creek Group) and Mallina Formation (De Grey Group) outcrop in a linear belt within the Tabba Tabba Shear Zone in the northwest of CARLINDIE.

Components of the Carlindi Granitoid Complex range in age from c. 3488 to 2860 Ma and consist of at least four main age groupings, at c. 3490–3420, c. 3250, c. 2940, and c. 2860 Ma. Beryl, tantalum, and tin are present in pegmatites associated with the latter suite in the western part of CARLINDIE. The unexposed Pippingarra Granitoid Complex occupies a small part of the northwestern corner of CARLINDIE.

Seven sets of structures are recognized in the basement granite–greenstone terrane on CARLINDIE, and are divided into four main deformation events. D_1 deformation involved synvolcanic doming at c. 3467 Ma and the development of a disconformity between the Duffer and Panorama Formations of the Warrawoona Group. Folded leucosome veins in the Carlindi Granitoid Complex also formed at this time, and greenstones were further tilted prior to deposition of the unconformably overlying Strelley Pool Chert of the Warrawoona Group at c. 3426–3350 Ma. D_2 deformation at c. 3325–3300 Ma involved three discrete events on CARLINDIE: D_{2a} local tilting of Euro Basalt before deposition of the Wyman Formation; D_{2b} extensional growth faulting during deposition of the Wyman Formation at c. 3325–3315 Ma; and D_{3c} tight folding of greenstones after deposition of the Wyman Formation, at c. 3310 Ma. Deposition of the Sulphur Springs Group was accompanied by tilting of greenstones (D_{3a}) and granitic intrusion, followed by D_{3b} growth faulting during deposition of the Gorge Creek Group. D_4 deformation started with tilting of greenstones in the Warralong greenstone belt and amphibolite-facies sinistral shear deformation in the Tabba Tabba Shear Zone (D_{4a}), probably at c. 2970–2955 Ma. This was followed by the main period of regional sinistral transpression (D_{4b}) at c. 2940–2930 Ma that affected the whole area of CARLINDIE, but was particularly strongly manifested in the Tabba Tabba Shear Zone in the northwest of CARLINDIE, and in the Lalla Rookh – Western Shaw Structural Corridor in the southeast of CARLINDIE, and accompanied deposition of the De Grey Group.

The granite–greenstone terrain of the northern part of the Pilbara Craton is unconformably overlain by the lower formations of the Neoarchaean Fortescue Group of the Mount Bruce Supergroup. The Fortescue Group includes basal coarse clastic rocks of the Bellary Formation, the overlying Mount Roe Basalt, the Hardey Formation, and the Kylena Formation. A single occurrence of anomalous gold was assayed in conglomerate at the basal unconformity of the group. These rocks have been affected by five phases of deformation prior to being cut by two swarms of dolerite dykes belonging to the c. 755 Ma Mundine Well dyke swarm and the younger, but undated, Round Hill dyke swarm. Quartz veining in fractures and faults accompanied dyke emplacement.

KEYWORDS: Archaean, Pilbara Supergroup, Warralong greenstone belt, Carlindi Granitoid Complex, Fortescue Group, lithostratigraphy, geochronology, structure, metamorphism, mineralization.

Introduction

These Explanatory Notes describe the regional geological setting, lithostratigraphy, structure, metamorphism, geochronology, and mineralization of the CARLINDIE* 1:100 000 sheet (SF 50-4, 2756), based on regional mapping carried out between 2000 and 2002, using 1:25 000-scale colour aerial photographs together with interpretation of available regional magnetic and radiometric datasets. CARLINDIE covers the south-central part of the PORT HEDLAND – BEDOUT ISLAND 1:250 000 sheets (SF 50-4 and SE 50-16) between latitudes 20°30' and 21°00'S and longitudes 119°00' and 119°30'E in the northwestern part of the East Pilbara Granite–Greenstone Terrane (EPGGT) of the Pilbara Craton (Fig. 1; Tyler and Hocking, 2002). CARLINDIE lies within the East Pilbara Mineral Field and is underlain by Palaeoarchaean to Mesoarchaean (c. 3500–2940 Ma) volcanic, sedimentary, and granitic rocks of the EPGGT, and by unconformably overlying volcanic and sedimentary rocks of the Neoarchaean (c. 2770 Ma) Fortescue Group of the Mount Bruce Supergroup (MacLeod et al., 1963; Trendall, 1990, 1995). Cainozoic deposits cover extensive parts of the central and northern areas of the map sheet.

Access, land use, climate, and vegetation

The main access on CARLINDIE is provided by the sealed Port Hedland – Marble Bar Road that transects CARLINDIE from the northwestern corner to the east-southeast (Fig. 2). A well-maintained graded dirt track extends from the Marble Bar Road southward along the east bank of the Shaw River, to the North Pole area on NORTH SHAW. The Old Great Northern Highway in the far-northwestern corner of CARLINDIE is a well-maintained dirt road. The Old Marble Bar Road, in contrast, is degraded and overgrown and barely negotiable by four-wheel drive vehicle. Several intermittently maintained pastoral tracks cross other flat parts of CARLINDIE, but much of the rugged terrain in the southeast is only accessible by four-wheel drive vehicle or by foot traverse.

Carlindie Station is the only extant settlement on CARLINDIE and runs cattle. The Lalla Rookh Homestead is abandoned. Many permanent and temporary water holes in the granitic country in the southwest, some of the central rivers, and the rugged greenstone hills in the southeast contain potable water that is clear and sweet to drink. Ancient petroglyphs are common on granitic tors throughout CARLINDIE, indicating previous habitation by the nomadic Aborigines of the northwest.

CARLINDIE has an arid climate with an average annual rainfall of about 254 mm and an average annual evaporation of about 3600 mm (Pink, 1992), leaving the region dry during the late winter to early summer months. Rainfall is erratic, with little precipitation during the winter months of May and June, but the area is subject to floods during cyclonic and thunderstorm activity between December and March. Average summer temperatures range from daily maxima of about 30–40°C, whereas daily winter temperatures typically vary between 12°C and about 30°C (Pink, 1992). The prevailing winds blow from the east and southeast.

Several species of spinifex grass (*Triodia*) grow on CARLINDIE, with the largest species inhabiting creek beds or their banks. Elsewhere, the size and species of spinifex depends on the availability of near-surface water and when the area was last burned. Sandy areas and some valleys contain *Grevillea*, wattles (*Acacia*), soft shrubs (*Crotalaria*), eucalypts, tea tree (*Melaleuca*), and Sturt Desert Pea. Creeks and rivers contain large eucalypts and grasses, and areas of rock outcrop include small shrubs, grasses, mulga, stunted eucalypts, and fig trees. Mixed outcrop and colluvium have spinifex, small shrub, grasses, and *Acacia*.

Physiography

The physiography of CARLINDIE is divisible into three broad regions (Fig. 2). The rugged southeast part of the map is underlain by the Warralong and Panorama greenstone belts and the Lalla Rookh Sandstone that outcrop as strike-controlled ridges and valleys. Granitic rocks of the Carlindi Granitoid Complex outcrop as more subdued, undulating topography in the southwest. The central and northern parts of CARLINDIE are flat colluvial–alluvial sandplains transected by several large rivers that drain northward into the Indian Ocean. The highest point elevation is 369 m above mean sea level (AMSL; MGA 755940E 7677260N) in the Panorama greenstone belt in the southeastern corner of CARLINDIE. The lowest point elevation is 46 m AMSL in the northernmost part of CARLINDIE (MGA 723740E 7731560N).

Previous investigations

Noldart and Wyatt (1962) and Hickman (1983) provided details of the early history of exploration, mining, and geological studies in the Pilbara Craton, including the PORT HEDLAND – BEDOUT ISLAND 1:250 000 sheet area on which CARLINDIE is located.

Hickman and Gibson (1981) mapped the PORT HEDLAND – BEDOUT ISLAND 1:250 000 sheet (second edition) in 1975–1977 during a Geological Survey of Western Australia (GSWA) – Bureau of Mineral Resources (BMR, now Geoscience Australia) mapping program in the east Pilbara. The main area of granite–greenstone rocks in the northern part of the Pilbara Craton was then referred to as the 'Pilbara Block', the geology of which was described by Hickman (1983, 1984). This terminology was later changed so that the area of granite–greenstone rocks in the northern part of the Pilbara Craton was referred to as the 'northern Pilbara granite–greenstone terrane' (Griffin, 1990), and then the 'North Pilbara Terrain' (Van Kranendonk et al., 2002), and the craton was defined as including both the basement granite–greenstone rocks and overlying Hamersley Basin (Trendall, 1990).

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

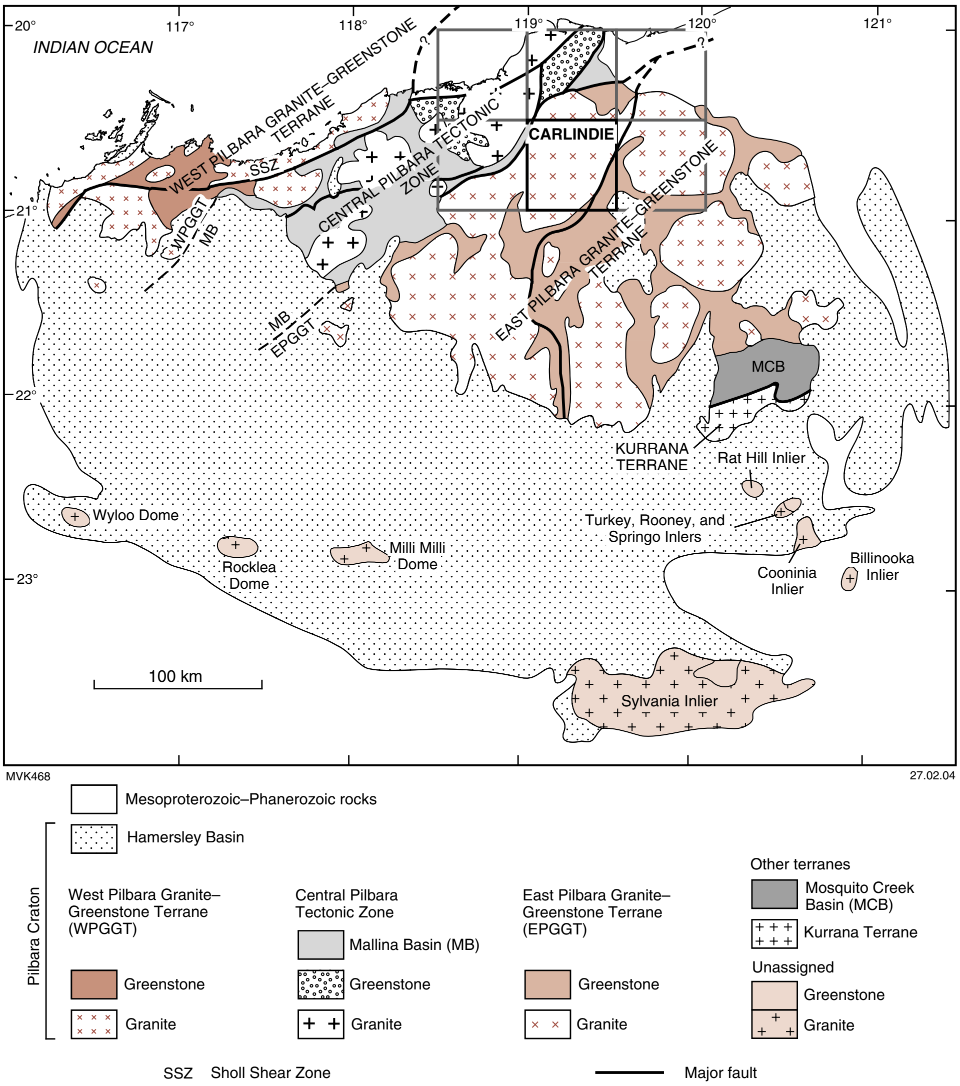

Figure 1. Simplified geology of the Pilbara Craton, showing the location of the Carlindie 1:100 000 sheet and the Port Headland 1:250 000 sheet

However, the use of 'terrain' is confusing because geological terranes have now been recognized within this area (see below), so this northern area of basement granite–greenstone rocks is herein referred to as the northern part of the Pilbara Craton, which contains five lithotectonic units, the central and largest of which is the East Pilbara Granite–Greenstone Terrane (Hickman, 2001; Van Kranendonk et al., 2002).

Hickman (1983) grouped the oldest volcano-sedimentary rocks across the 'Pilbara Block' into the 'Archaean Pilbara Supergroup' and proposed that the lower part of the supergroup formed a single, layer-cake stratigraphy that was divided into the Warrawoona, Gorge Creek, and Whim Creek Groups. The major tectonic structures of the region were interpreted as the result of solid-state diapirism of the Archaean granitic complexes (Hickman, 1983, 1984). The lithostratigraphy of the Pilbara Supergroup was modified by Hickman (1990) to separate the De Grey Group from the Gorge Creek Group. A major revision was made by Hickman (1997) to distinguish the greenstone succession of the west Pilbara from those of the east Pilbara, as suggested by previous geochronology (e.g. Horwitz and Pidgeon, 1993) and supported by subsequent data (Smith et al., 1998; Sun and Hickman, 1998; Van Kranendonk et al., 2002; Smith, 2003). Recent work has also identified separate stratigraphic components in the east Pilbara, including the Coonterunah and Sulphur Springs Groups (Buick et al., 1995, 2002; Van Kranendonk and Morant, 1998; Van Kranendonk, 2000). Following further mapping and geochronology, Van Kranendonk et al. (2002) redefined the Warrawoona Group so that the Duffer Formation was included in the Talga Talga Subgroup; the Apex Basalt, Panorama Formation, and Strelley Pool Chert were ascribed to the Salgash Subgroup; and the Euro Basalt, Wyman Formation, and Charteris Basalt were ascribed to the Kelly Subgroup.

Granitic rocks of the northern part of the Pilbara Craton form broad, domical complexes consisting of multiple phases that intruded from c. 3490 to 2830 Ma

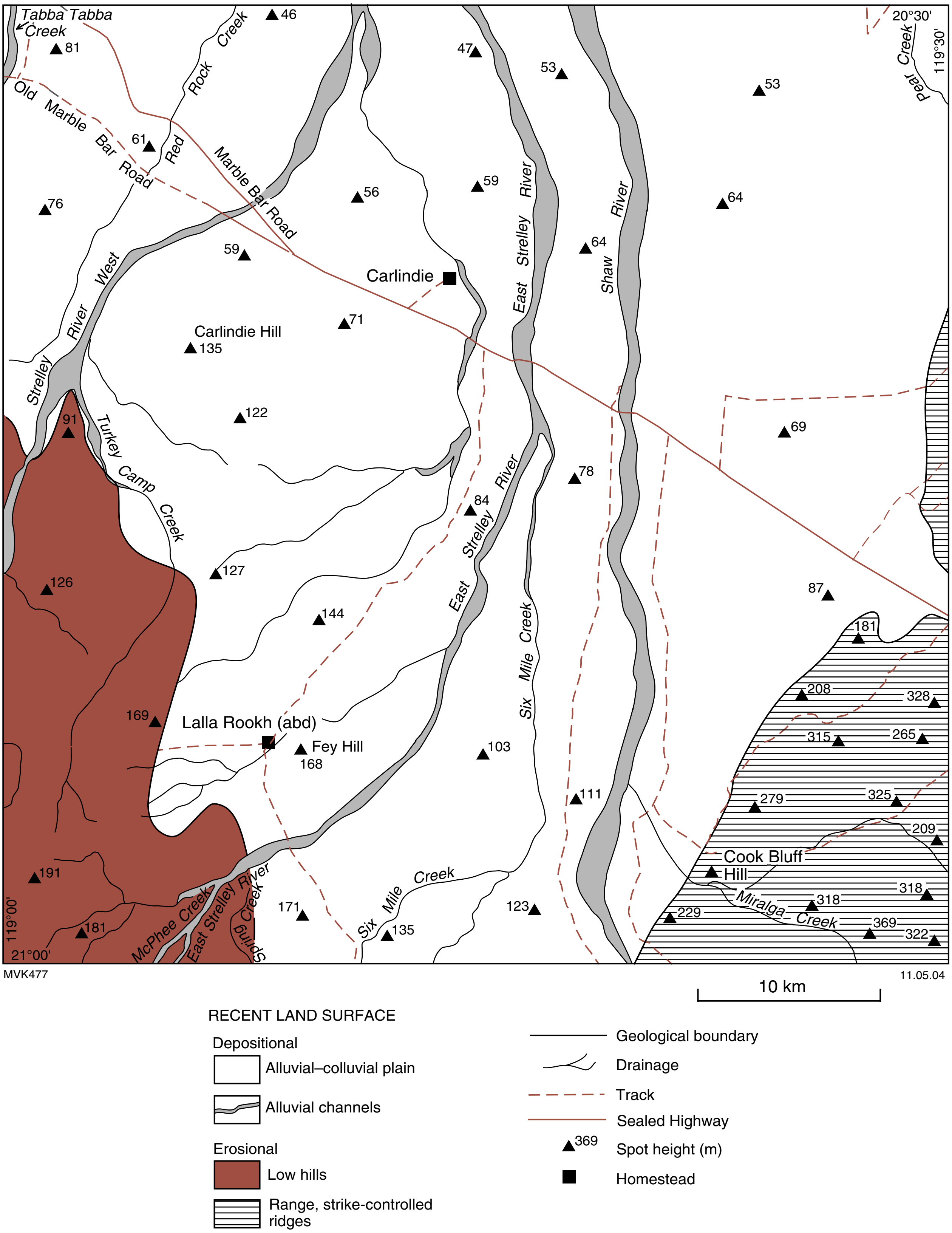

Figure 2. Physiographic features of CARLINDIE

(see data in Van Kranendonk et al., 2002; Nelson, in prep.a). Bickle et al. (1983) described the c. 3467 Ma, calc-alkaline North Shaw Suite in the Shaw Granitoid Complex and compared them favourably with Phanerozoic calc-alkaline igneous suites in subduction settings (age data from Nelson, 2000 and Nelson, D. R., written comm., 2003). However, Smithies (2000) showed that the compositions are incompatible with an origin from slab melting in a modern-style steep subduction setting and suggested instead that the early (c. 3490–3430 Ma) tonalite–trondhjemite–granodiorite (TTG) rocks were more likely to have been generated by melting of mafic lower crust. Geochemical evidence that syn- to post-tectonic suites of granitic rocks (c. 3320–2830 Ma) were derived by partial melting of pre-existing sialic crust has been presented by Hickman (1983 and references therein), Bickle et al. (1989), and Collins (1993).

A detailed diapiric model of structural evolution has been proposed for the Mount Edgar Granitoid Complex of the EPGGT (Hickman, 1984; Collins, 1989; Williams and Collins, 1990; Collins et al., 1998; Collins and Van Kranendonk, 1999). This model has been applied to the rest of the EPGGT (Van Kranendonk et al., 2002, in press; Hickman and Van Kranendonk, 2004), with diapirism occurring during multiple thermotectonic events throughout the history of the terrane to c. 2760 Ma.

Bickle et al. (1985) challenged the solely diapiric model for the tectonic evolution of the EPGGT and suggested that an early period of Alpine-style thrusting affected the western part of the Shaw Granitoid Complex. Zegers et al. (1996, 2001) proposed that this thrusting, which was interpreted to have occurred before c. 3470 Ma, produced an overthickened crust that experienced extensional collapse at c. 3467 Ma, when the domical granitic complexes rose as metamorphic core complexes. Similar core complex models involving early thrusting and later extensional collapse were developed for the Mount Edgar Granitoid Complex and structures in adjacent greenstones, but at c. 3300 Ma (van Haaften and White, 1998; Kloppenburg et al., 2001). Blewett (2001) re-introduced a cross-folding model (first proposed by Noldart and Wyatt, 1962) for the formation of the dome-and-syncline structure of the EPGGT, but did not explain the contrary evidence in favour of a diapiric origin for these structures.

Tectonic models of horizontal tectonic accretion and core complex formation in the structural development of the EPGGT have been challenged by several recent studies based on detailed mapping and geochronology (Van Kranendonk et al., 2001a, 2001b, 2002, in press; Hickman and Van Kranendonk, 2004). These authors showed that the stratigraphic type section of the Warrawoona Group in the Marble Bar greenstone belt is a right-way-up, upward-younging, autochthonous succession affected by diapirism of the granitic complexes.

Blake (1993, 2001) applied sequence-stratigraphic principles to the stratigraphy of the Mount Bruce Supergroup that unconformably overlies the EPGGT and includes the Fortescue Group, whereas Thorne and Trendall (2001) retained a strictly lithostratigraphic nomenclature in their overview of the Fortescue Group.

Regional geological setting

The Pilbara Craton of northwestern Australia has an exposed area of about 183 000 km^2 and consists of a basement of Archaean (3655–2830 Ma) granitic rocks and greenstones that outcrop in several inliers beneath an unconformably overlying, Neoarchaean to Palaeoproterozoic (2770–2400 Ma) cover sequence (Mount Bruce Supergroup) in the Hamersley Basin (Trendall, 1990). The largest of the basement inliers forms the northern part of the Pilbara Craton, which is subdivided into five lithotectonic domains (Fig. 1; Van Kranendonk et al., 2002).

CARLINDIE is in the northwestern part of the EPGGT in the northern part of the Pilbara Craton (Fig. 1). CARLINDIE is primarily underlain by the Carlindi Granitoid Complex, but includes the following: the southwestern part of the Warralong greenstone belt in the southeast (17 on Fig. 3); the northern part of the Panorama greenstone belt in the far southeast (7 on Fig. 3); the Lalla Rookh Synclinorium in the south (20 on Fig. 3); and strongly sheared rocks in the Tabba Tabba Shear Zone in the northwestern corner (Figs 3 and 4). Neoarchaean volcanic and sedimentary rocks of the Fortescue Group of the Mount Bruce Supergroup outcrop in the northwestern part of the Marble Bar Sub-basin in the southeastern part of CARLINDIE. The geological evolution of rocks on CARLINDIE is summarized in Table 1.

The Warralong greenstone belt comprises amphibolite- to greenschist-facies volcanic and sedimentary rocks of the c. 3515–3500 Ma Coonterunah Group, the c. 3490–3310 Ma Warrawoona Group, the c. 3240 Ma Sulphur Springs Group, the younger-than-3235 Ma Gorge Creek Group, and the c. 2970–2940 De Grey Group, the latter four lying on older groups across erosional unconformities (Fig. 4). The lower parts of the stratigraphy are intruded and locally contact metamorphosed to hornblende-hornfels facies by granitic rocks of the c. 3485–2860 Ma Carlindi Granitoid Complex. The Neoarchaean Fortescue Group (c. 2775–2630 Ma) is the oldest component of the Mount Bruce Supergroup in the Hamersley Basin (Trendall, 1990) and outcrops in the northwestern corner of the Marble Bar Sub-Basin in the southeastern part of CARLINDIE (Fig. 4). The Fortescue Group lies on older rocks of the EPGGT across an erosional unconformity.

The EPGGT is dominated by two distinct types of structures (Van Kranendonk et al., 2002). One type is related to the long-lived, but punctuated, formation of the dome-and-basin map pattern, whereas the other type is related to c. 2940 Ma regional sinistral transpression (Collins, 1989; Van Kranendonk and Collins, 1998; Zegers et al., 1998; Hickman and Van Kranendonk, 2004; Van Kranendonk et al., 2002, in press). The earliest regional deformation (D_1) is identified as tilted, and locally folded bedding in Coonterunah and Warrawoona Group rocks that are unconformably overlain by the c. 3426–3350 Ma Strelley Pool Chert of the upper part of the Warrawoona Group (Buick et al., 1995; Van Kranendonk et al., 2002; age data from Nelson, 2001, in prep.a, in prep.b). D_1 is also manifest as

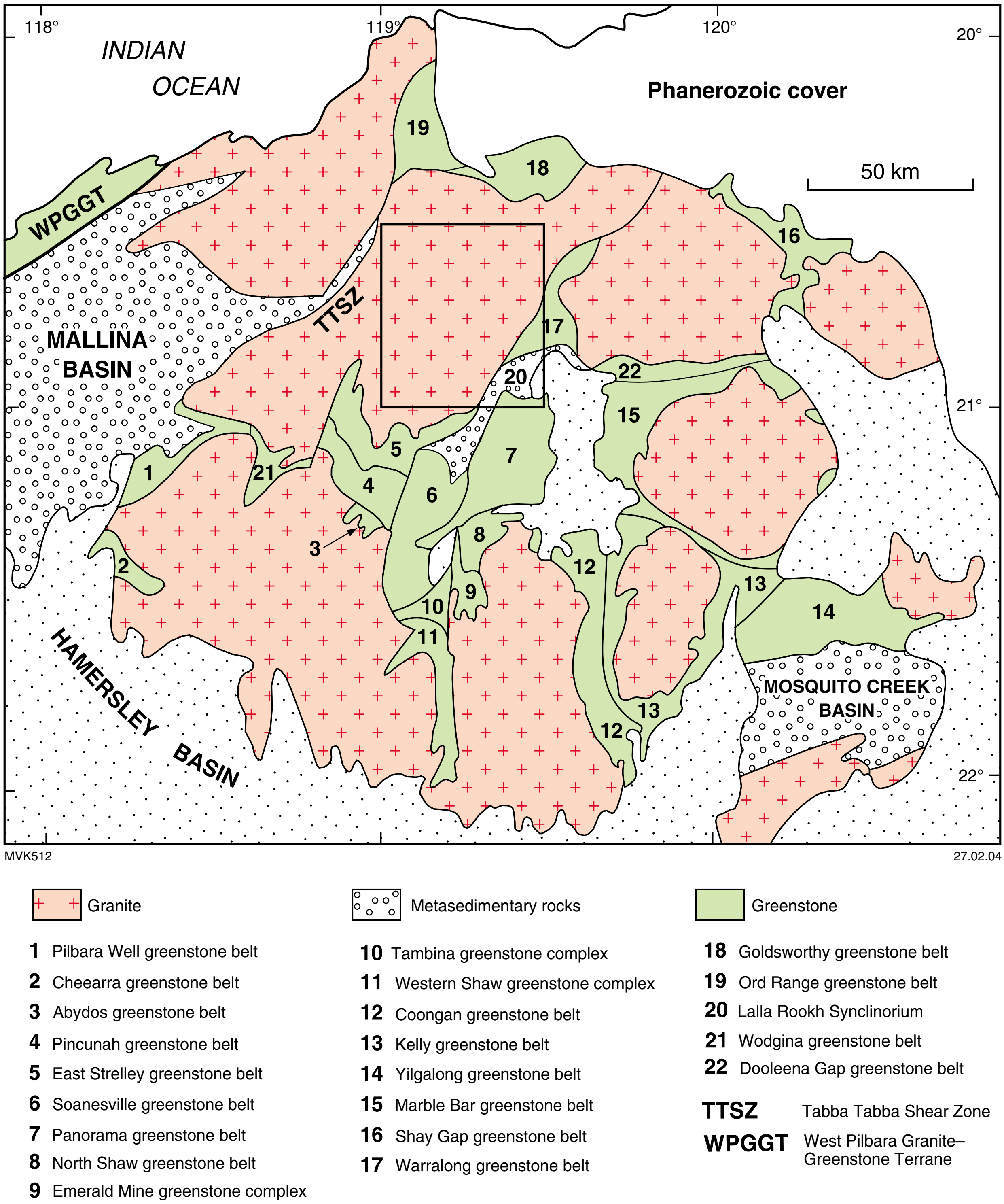

Figure 3. Diagrammatic sketch of the East Pilbara Granite–Greenstone terrane, showing the position of CARLINDIE relative to lithostructural features (modified from Van Kranendonk et al., 2002)

folded leucosome veins in c. 3485–3467 Ma granitic rocks, generated at c. 3450 Ma and cut by nonmigmatitic, c. 3430 Ma granitic rocks (Van Kranendonk, 2003a). Widespread D_2 folding of the Warrawoona Group occurred during intrusion of a voluminous suite of crustally-derived granitic rocks at 3325–3310 Ma that were coeval with felsic volcanism of the Wyman Formation at the top of the group. This deformation caused a major component of doming of the granitic complexes in the eastern part of the EPGGT (Collins, 1989; Collins et al., 1998; Van Kranendonk et al., 2002, in press). Deposition of the c. 3255–3235 Ma Sulphur Springs Group, associated granitic magmatism, and renewed partial convective crustal overturn caused D_3 deformation. Regional D_4 deformation involved regional

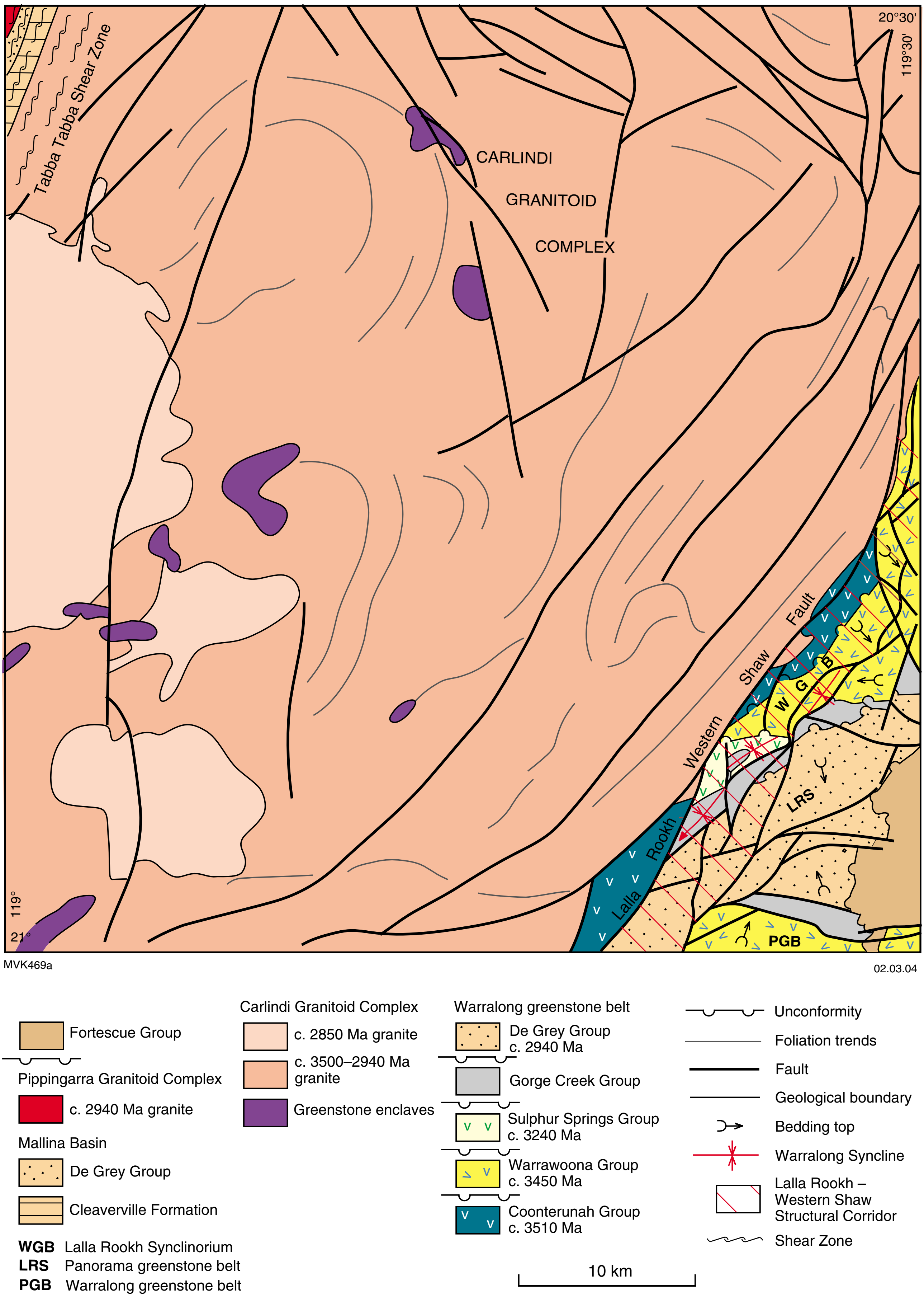

Figure 4. Simplified geology of Carlindie, showing major lithotectonic and structural elements

Table 1. Summary of the major geological events on CARLINDIE

Age range (Ma)	*Geological events*
c. 3515–3500	Deposition of the Coonterunah Group
c. 3490–3430	Deposition of the Talga Talga and Salgash Subgroups of the Warrawoona Group and intrusion of early phases in Carlindi Granitoid Complex
c. 3470–3430	Early, synvolcanic doming (D_1) and amphibolite- to greenschist-facies metamorphism of greenstones
c. 3350–3315	Deposition of the Kelly Subgroup of the Warrawoona Group accompanied by local tilting of greenstones (D_{2a} deformation) and growth faulting (D_{2b})
c. 3315–3310	Major D_{2c} deformation during partial convective overturn of the middle- to upper crust; widespread granitic magmatism and metamorphism
c. 3255–3235	Deposition of the Sulphur Springs Group, associated granitic magmatism (*AgLmh*), metamorphism, and deformation (D_{3a})
c. 3235–?3020	Deposition of the Gorge Creek Group (Soanesville Subgroup) during local extensional deformation (D_{3b})
c. 2970–2955	Deposition of the lower De Grey Group (Mallina Formation); intrusion of granites in the Pippingarra and Carlindi Granitoid Complexes; intrusion of ultramafic and mafic rocks in the Mallina Basin; D_{4a} shear deformation in Tabba Tabba Shear Zone, tilting of greenstones, and amphibolite-facies metamorphism
c. 2940–2930	Deposition of the De Grey Group before, and during, D_{4b} regional sinistral transpression (including Tabba Tabba Shear Zone and Lalla Rookh – Western Shaw structural corridor); greenschist- to amphibolite-facies metamorphism
c. 2860	Intrusion of the post-tectonic Kimmys Bore and Kadgewarrina Monzogranites in the Carlindi Granitoid Complex, and associated Sn–Ta–Brl mineralization
<2830, >2772	Deposition of the Bellary Formation of the Fortescue Group, followed by folding during north–south compression (D_{F1})
c. 2772	Deposition of the Mount Roe Basalt during east–west extension (D_{F2}), followed by folding and faulting (D_{F3})
c. 2764–2756	Deposition of the Hardey Formation, followed by gentle folding (D_{F4})
c. 2740	Deposition of the Kylena Formation and intrusion of dolerite sills (*AF(d)*) and possibly of some undated dolerite dykes (*d*)
<2740	Faulting and folding of the Fortescue Group (D_{F5})
c. 755	Intrusion of southwest–northeast striking Mundine Well dyke swarm (*Edw*) and northwest–southeast striking Round Hummock dyke swarm (*Edo*)
	Faulting

sinistral transpression at c. 2940 Ma across the whole of the northern part of the Pilbara Craton (Van Kranendonk et al., 2002) and caused tight folding of all groups in the EPGGT, including the syntectonic De Grey Group (Van Kranendonk and Collins, 1998). This was followed by local shear deformation at c. 2890 Ma (Baker et al., 2002) and then the intrusion of post-tectonic granitic rocks at 2860–2830 Ma that represents the final period of stabilization of the northern part of the Pilbara Craton. Uplift and erosion was then followed by deposition of the Fortescue Group and by at least five phases of deformation that accompanied and post-dated deposition of this group.

Archaean rocks of the northern part of the Pilbara Craton

Archaean volcano-sedimentary rocks of the northern part of the Pilbara Craton belong to the Pilbara Supergroup (Hickman, 1983). These rocks have been subdivided into five lithostratigraphic groups and two unassigned formations (Van Kranendonk et al., 2002):

- the c. 3515–3500 Ma Coonterunah Group (Buick et al., 1995; Van Kranendonk and Morant, 1998);
- the c. 3490–3310 Ma Warrawoona Group (Lipple, 1975; Hickman, 1977a, 1983, 1990; Van Kranendonk et al., 2002);
- the <3308 Ma Budjan Creek Formation (Bagas et al., 2003; not on CARLINDIE);
- the ≤3270 Ma Golden Cockatoo Formation (Van Kranendonk and Morant, 1998; Nelson, in prep.b; not on CARLINDIE);
- the c. 3255–3235 Ma Sulphur Springs Group (Van Kranendonk and Morant, 1998; Buick et al., 2002);
- the <3235 to >2940 Ma Gorge Creek Group (Lipple, 1975; Hickman, 1977a, 1983, 1990);
- the c. 2970–2940 Ma De Grey Group (Hickman, 1990; Smithies et al., 2001).

Deposition of this autochthonous stratigraphic succession was punctuated by suites of synvolcanic intrusions and synvolcanic and syntectonic granitic rocks within the Carlindi Granitoid Complex, whose components have been subdivided into four main age groupings, including:

- an early synvolcanic tonalite–trondhjemite–granodiorite suite that ranges in age from 3484 to 3469 Ma;
- a foliated monzogranite associated with the Sulphur Springs Group, dated at c. 3252 Ma;
- a syntectonic suite of predominantly leucocratic monzogranites at c. 2940 Ma;
- post-tectonic, highly fractionated monzogranites dated at c. 2860 Ma.

Coonterunah Group

Rocks ascribed to the Coonterunah Group on CARLINDIE are at amphibolite to upper-greenschist metamorphic grade, and vary from tectonic schists along the western margin of the belt at the contact with the Carlindi Granitoid Complex to undeformed rocks further within the greenstone belt. The group reaches a maximum preserved thickness of 1.75 km on CARLINDIE, but this is not the maximum depositional thickness because the lower part of the group has been tectonically flattened and intruded by granitic rocks, and the top is an erosional unconformity with the Strelley Pool Chert.

Table Top Formation (*AOtbas*, *AOtb*, *AOtccw*, *AOtccj*)

The structurally and stratigraphically lowest rocks of the Coonterunah Group are amphibolite schists with interbedded chert layers that are part of the Table Top Formation. Most of the mafic rocks near the granite contact are amphibolite schists (*AOtbas*) with a well-developed foliation and lineation defined by elongate crystals of metamorphic hornblende and plagioclase. Screens of bleached and silicified metabasalts (*AOtb*) within a younger, dated unit of quartz- and feldspar-porphyry of the overlying Coucal Formation (*AOcfr*: see below) are undeformed and display good pillow structures that indicate facing directions to the southeast (MGA 753800E 7692800N). Cherts interbedded with the metabasalts and amphibolite schists include varieties with centimetre-scale grey, blue, and white layering (*AOtccw*) and those with red and white layering (*AOtccj*), both of which show evidence of silicification by grey to blue-black chert veins. The protoliths for these cherts were not precisely determined, but a lack of clastic texture or contrary evidence suggests that the cherts may represent primary chemical sediments.

Coucal Formation (*AOcfrp*, *AOcfr*)

Intruding the Table Top Formation is a massive feldspar- and quartz-porphyritic rhyodacite (*AOcfrp*), which represents a subvolcanic sill to the more variegated, immediately overlying felsic volcaniclastic rocks (*AOcfr*) of the Coucal Formation. The rhyodacite sill contains 5–10% (visual estimate) zoned, sericitized euhedral feldspar phenocrysts up to 5 mm long. The groundmass is very fine grained quartz and sericite, with minor opaque minerals. Rocks interpreted as felsic volcanic extrusives (*AOcfr*) show more variable texture, including up to 10 m of faintly layered volcaniclastic rocks and bedded quartz-rich sandstone near the top. The principal lithology in this map unit is a massive rock with an aphanitic, pale-grey matrix enclosing 1 mm quartz and 2–4 mm feldspar phenocrysts. In thin section the feldspar phenocrysts are commonly completely replaced by fine-grained sericite and K-feldspar, with outer margins affected by limonite alteration. Some phenocrysts contain minor relicts of original (?K-)feldspar. The fine-grained groundmass has the appearance of devitrified glass and shows evidence of igneous flow foliation. An intrusive relationship of the lower part of the unit is inferred from the local crosscutting nature of the rhyolite in footwall pillowed basalt and chert (e.g. MGA 755000E 7694500N) and from the massive, coarsely porphyritic texture of the rock.

Warrawoona Group

Rocks of the Warrawoona Group outcropping in the Warralong and Panorama greenstone belts (Fig. 4) are at greenschist-facies metamorphic grade. They vary from essentially undeformed to high-strain metamorphic schists, although the majority are affected by very low strain.

Talga Talga Subgroup

Rocks of the Talga Talga Subgroup of the Warrawoona Group outcrop in the Warralong greenstone belt (around MGA 7590000E 7692500N). They are west facing and overturned, and unconformably overlain by the Gorge Creek Group to the south. The subgroup includes mafic schists of the Mount Ada Basalt, and felsic volcaniclastic rocks of the Duffer Formation, all weakly metamorphosed to greenschist facies. Older rocks of the subgroup outcrop on the adjacent COONGAN sheet (Van Kranendonk, 2004).

Mount Ada Basalt (AWmbks, AWmccw)

Small, low outcrops of strongly sheared chlorite–carbonate schist (*AWmbks*) and layered grey and white chert (*AWmccw*) in the northern part of the Warralong greenstone belt (759500E, 7700000N) are interpreted to belong to the Mount Ada Basalt based on lithostratigraphic relationships on the adjacent COONGAN sheet. The mafic schists are strongly foliated to schistose, whereas cherty rocks are recrystallized to a medium-grained mosaic of interlocking quartz crystals. Both units are folded about northerly plunging axes parallel to metamorphic mineral elongation lineations.

Duffer Formation (AWdstv, AWdft, AWdstq, AWdcc)

The Duffer Formation is up to 700 m thick on CARLINDIE, but this is a minimum estimate because the base is cut out by a fault (MGA 759500E 7692500N). On CARLINDIE the formation consists predominantly of massive to weakly bedded felsic volcaniclastic sandstone (*AWdstv*) and tuffaceous sandstone (*AWdft*) near the base, and quartz-rich sandstones (*AWdstq*) near the top. The lower map unit (*AWdstv*) is up to 450 m thick, with poorly defined beds (roughly 3–5 m thick) that have 30 cm-thick tops defined by finer grained rocks. Some rhyodacite flows are up to

5 m thick. The main lithology of this unit is a quartz- and feldspar-crystal-rich volcaniclastic rock, with lithic (chert) fragments up to 2 cm (Fig. 5a). Quartz crystals (Fig. 5b) are commonly euhedral bipyramids (Fig. 5c), although some show evidence of resorption and others are fragments. Altered feldspar crystals and lithic fragments account for up to 25% of the rock, which also contains altered biotite phenocrysts (Fig. 5d). The rock matrix is largely microcrystalline to cryptocrystalline quartz and minor sericite that is presumably after glassy particles. The unit is cut by numerous blue-black to grey hydrothermal chert veins, up to 60 cm across.

In the middle of the tuffaceous lower unit is 50 m of volcaniclastic rocks (*AWdft*) that vary from sand and silt beds with sparse, larger rip-up clasts of siltstone (to 4 cm), to mudstones and greenish-grey cherty porcellanites. Both reverse and normal graded bedding are preserved. Beds are commonly 6 cm thick, but there are beds 30 cm thick. Overall, this unit fines upward and is capped by grey and white cherts with 1 cm-thick bedding that are interpreted as silicified, fine-grained ash (not shown on map). The northern part of this unit is 20 m thick, consisting of milky white and blue-black chert (*AWdcc*) with poorly defined bedding, and minor quartz-rich sandstone.

Overlying the tuffaceous rocks is up to 200 m of white, quartz-rich sandstone and volcaniclastic quartz arenite (*AWdstq*). Quartz-rich sandstones at the base are interbedded with a 2 m-thick bed of massive volcaniclastic conglomerate that has well-rounded pebbles and boulders of quartzite, up to 20 cm in diameter, in a felsic volcaniclastic matrix. Bedding in the sandstones is conspicuous and generally 30 cm to 1 m thick. The sandstones contain granules of black chert and are cut by blue-black hydrothermal chert veins.

A sample of bedded crystal-lithic felsic tuff (GSWA 168996, part of *AWdstv*) was dated by U–Pb SHRIMP on zircons and returned a main population of zircons at 3477 ± 5 Ma (Nelson, 2002), which is the maximum depositional age of the rock (Table 2).

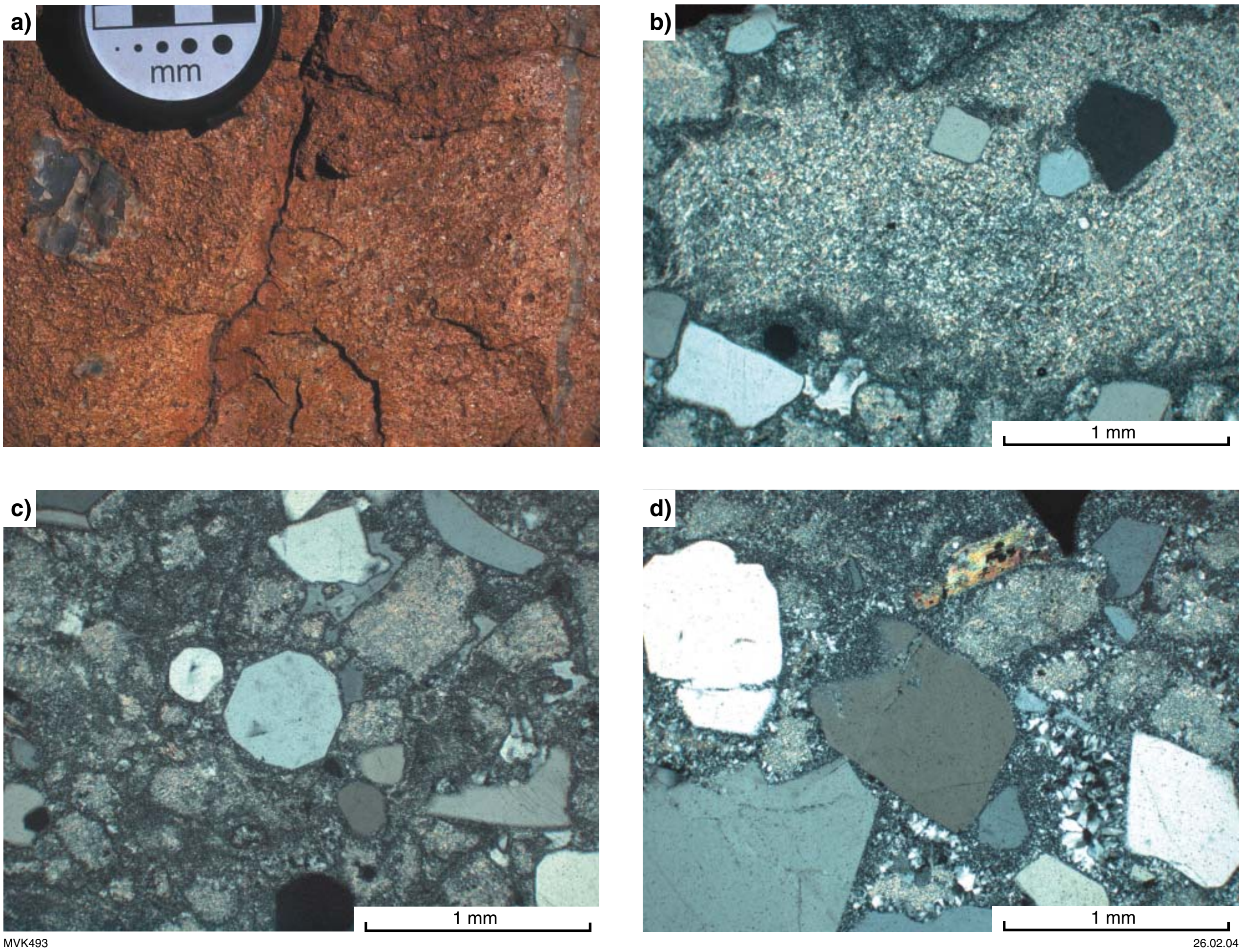

Figure 5. Volcaniclastic tuff of the Duffer Formation (*AWdstv*): a) outcrop, showing quartz-crystal-rich nature of the rock and a large, rounded chert fragment (GSWA 168996; MGA 759600E 7693400N); b) photomicrograph, in cross-polarized light, of a large fragment of rhyolite containing quartz phenocrysts, and isolated quartz phenocrysts fragments in the matrix (MGA 759300E 7693000N); c) photomicrograph, in cross-polarized light, showing euhedral and anhedral quartz crystal and crystal fragments with numerous fragments of sericite-altered felsic volcanic rock in a silicified groundmass (MGA 759300E 7693000N); d) photomicrograph, in cross-polarized light, showing several quartz-crystal fragments and an altered biotite crystal in a matrix of recrystallized quartz (MGA 758900E 7692250N)

Table 2. Summary of U–Pb SHRIMP geochronology results from Carlindie

GSWA number	*Locality (MGA) Easting*	*Northing*	*Lithology*	*Age (Ma)*	*(number of zircons)*	*Interpretation*	*Reference*
168995	755210E	7694250N	Quartz-phenocrystic rhyolite; Coucal Formation, Coonterunah Group (*AOcfr*)	3498 ± 2	(14)	?Igneous eruption age	Nelson (2002)
168996	759540E	7693420N	Quartz-phenocrystic, crystal-lithic felsic tuff; Duffer Formation, Warrawoona Group (*AWdstv*)	3477 ± 5 3524 ± 4 3571 ± 6	(9) (2) (6)	Igneous eruption age Xenocrystic Xenocrystic	Nelson (2002)
142836	758720E (Coongan)	7692270N	White, quartz-rich sandstone; Strelley Pool Chert, Warrawoona Group (*AWsstq*)	3426 ± 10 3602 ± 5	(7) (24)	Detrital Detrital	Nelson (1998)
168994	756300E	7690920N	Fine-grained, well-bedded tuff of probable felsic composition; Euro Basalt, Warrawoona Group (*AWeft*)	c. 2760		Hydrothermal	D. R. Nelson (written comm., 2001)
168993	751650E	7689200N	White quartz-rich sandstone; Wyman Formation, Warrawoona Group (*AWwstq*)	3508 ± 3	(30)	Inherited	Nelson (2002)
168992	749980E	7689420N	Blue-grey chert-pebble sandstone; Wyman Formation, Warrawoona Group (*AWwstq*)	3324 ± 4 3603 ± 5		Age of deposition Detrital	Nelson (2002)
168989	749170E	7687070N	Quartz-rich sandstone lens; Kunagunarrina Formation, Sulphur Springs Group (*ASksc*)	3423 ± 8 3491 ± 4 3514 ± 7	(5) (19) (6)	Detrital Detrital Detrital	Nelson (2002)
168991	749170E	7687070N	Felsic volcaniclastic sandstone; Kangaroo Caves Formation, Sulphur Springs Group (*AScsv*)	3496 ± 4 3524 ± 10	(19) (1)	Inherited Inherited	Nelson (2002)
178040	734600E	7698100N	Foliated biotite monzogranite; Carlindi Granitoid Complex (*AgLmh*)	3252 ± 4	(17)	Igneous	Nelson (in prep.b)
168997	762160E (Coongan)	7693550N	Quartz-rich sandstone; Corboy Formation, Gorge Creek Group (*AGcstq*)	3410 ± 6 3481 ± 20 3582 ± 13	(24) (1) (1)	Detrital Detrital Detrital	Nelson (2002)
168990	748010E	7684310N	Quartz-rich sandstone; Paddy Market Formation, Gorge Creek Group (*AGpstq*)	3419 ± 12 3459 ± 7 3496 ± 2	(1) (1) (27)	Detrital Detrital Detrital	Nelson (2002)
160745	709790E	7727360N	Strongly foliated, fine-grained biotite granodiorite; Carlindi Granitoid Complex (*AgLmm*)	2940 ± 3 3248 ± 12 3326 ± 7 3518 ± 11	(8) (3) (1) (3)	Igneous Inherited Inherited Inherited	Nelson (2001)
B20	718150E	7689250N	Crustally contaminated dolerite dyke of the Mundine Well dyke swarm (*Ꝑdw*)	c. 2760 2859 ± 2 (*AgLkb*) c. 3069 c. 3174 c. 3232 c. 3420 3488 ± 5	(3) (8) (1) (2) (1) (2) (2)	Inherited Inherited Inherited Inherited Inherited Inherited Inherited	Wingate and Giddings (2000); M. T. D. Wingate (written comm., 2003)

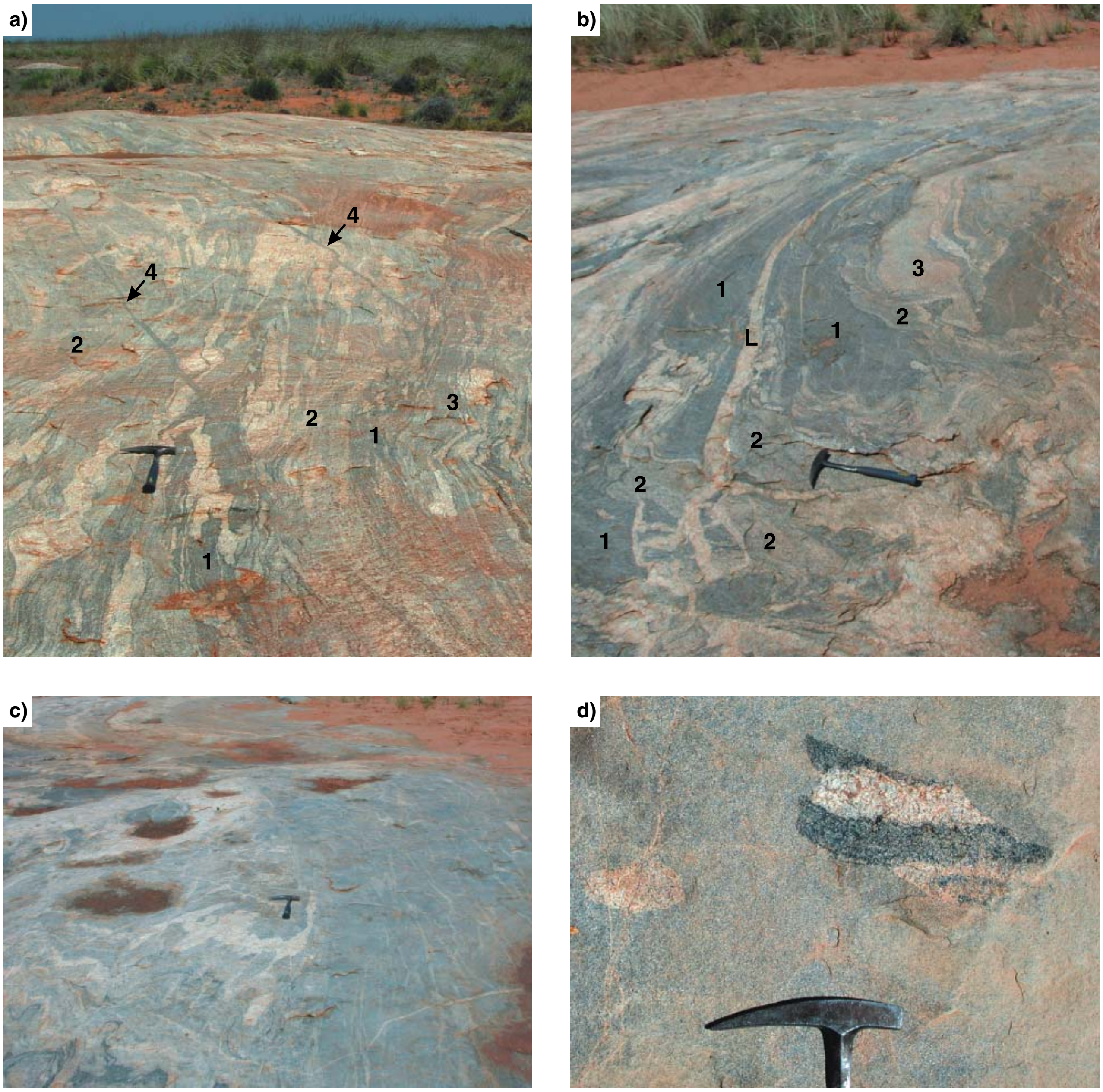

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Figure 6. The Wilson Well Gneiss (*AgLwi*; MGA 732250E 7702260N): a) typical exposure of multicomponent, migmatitic tonalitic orthogneiss (c. 3470 Ma, phases 1–3), cut by late veins of grey granite (4; probably c. 2940 Ma); b) folded, multicomponent tonalitic orthogneiss (c. 3470 Ma, phases 1–3) cut by axial-planar leucogranite (L, undated); c) tightly folded migmatitic tonalitic orthogneiss (left, probably c. 3470 Ma) cut by a more homogeneous, foliated, dark-grey granite (right, probably c. 3430 Ma); d) view, looking down on horizontal outcrop surface, of homogeneous monzogranite (?*AgLmh*; 3252 ± 4 Ma, Nelson, in prep.b) with xenolith of migmatitic orthogneiss (*AgLwi*)

Towers Formation (*AWtm*)

Layered grey, white, and red chert that is interpreted to represent part of the Marble Bar Chert Member of the Towers Formation (*AWtm*) forms a 20 m-thick cap to the Duffer Formation in the Warralong greenstone belt. The chert contains millimetre- to centimetre-thick layers of the different colours of chert, with local wavy textures forming small domes in places. The chert contains fine-grained clastic sediment locally.

Synvolcanic granitic rocks of the Carlindi Granitoid Complex (*AgLut*, *AgLutx*, *AgLwi*, *AgLg*, *AgLdq*, *AgLl*, *AgLlxn*, *AgLlr*)

The bulk of the Carlindi Granitoid Complex comprises a mixture of weakly deformed to migmatitic and gneissic TTG (see Interpreted bedrock geology diagram on main map). The Motherin Monzogranite (*AgLut, AgLutx*) outcrops along the western margin of the complex, but is more extensive on WALLARINGA (to the west) and WODGINA (to the southwest), where it has been described in detail by Blewett et al. (in prep.). This unit is heterogeneous, comprising variably quartz–feldspar-porphyritic, medium- to coarse-grained, biotite monzogranite to (hornblende–)biotite granodiorite, with common to abundant dyke rocks of various lithology. The unit is typically moderately to strongly foliated, although unfoliated rocks are locally present. The rocks are cryptically to strongly layered, and locally gneissic. Biotite-rich (8 to 15%) layers and schlieren are commonly folded. The Motherin Monzogranite is characterized by at least four phases of dykes or pods that include:

- foliated fine- to medium-grained equigranular biotite monzogranite to granodiorite;
- variably foliated biotite leucogranite;
- massive to moderately foliated, equigranular sparsely (quartz–)feldspar-porphyritic, locally muscovite-bearing, biotite monzogranite;
- multiple generations of pegmatitic granite.

Pegmatites, which locally form a common to very abundant component, are both concordant and discordant, and include both foliated and massive varieties. The granite unit also includes isolated greenstone xenoliths, and delineated regions of more common greenstone enclaves (largely amphibolite, peridotite, and ultramafic schists: *AgLutx*) can be separated at map scale. The main phases of the Motherin Monzogranite are magnetic (up to 600×10^{-5} SI units) and the intrusion is clearly defined on regional aeromagnetic images. Metamorphic grade is typically high (middle-amphibolite facies). A sample of the Motherin Monzogranite that has intruded the Coonterunah Group and been folded around the nose of the Pilgangoora Syncline on WODGINA has been dated by sensitive high-resolution ion microprobe (SHRIMP) U–Pb on zircon at c. 3475 Ma (Baker, D. E. L., University of Newcastle, written comm., 2001).

The Wilson Well Gneiss (*AgLwi*; Van Kranendonk, 2000) is a heterogeneous unit of weakly migmatitic TTG gneiss, containing sparse enclaves of homogeneous, medium-grained quartz diorite, and cut by numerous dykes of various texture and composition (Fig. 6). This unit is broadly similar to the Motherin Monzogranite, except it is commonly more sodic and may include younger granitic phases. Typically, the bulk of the unit is well foliated and contains less than 10% leucogranite veinlets (0.5 – 10 cm wide) that define a gneissic layering. The host rock is medium grained and completely recrystallized to an equigranular, granoblastic texture. Relicts of feldspar-porphyritic texture are locally preserved. In addition to enclaves of older amphibolite, as many as six intrusive granitic phases have been recognized. These include hornblende tonalite and component migmatite veins or local swarms of pegmatitic granite. Cutting these early phases is a homogeneous, medium-grained hornblende granodiorite to granite. These more voluminous components are cut by narrow dykes of strongly foliated, fine-grained grey granite whose fabric is syntectonic with emplacement, since neither older nor younger components contain this foliation. The fine-grained dykes are in turn cut by dykes of leucogranite and pegmatitic granite, and these are cut by dykes of schlieric, wispy-layered leucogranite. None of the younger intrusive phases in these outcrops can be confidently correlated with the main phases of the rest of the granitic complex. An attempt at dating the older gneissic tonalite on NORTH SHAW was unsuccessful, due to weathering. In thin section the tonalitic gneiss is composed of equigranular quartz and plagioclase, with about 5% tabular crystals of biotite. Quartz grain boundaries vary from sutured contacts to granoblastic triple-point contacts. There is minor chlorite and muscovite, and trace amounts of zircon and apatite. Monazite forms crystals up to 1 mm long that are metamict and rimmed by epidote.

Outcrops of homogeneous, leucocratic, equigranular biotite-hornblende granodiorite to monzogranite (*AgLg*) outcrop along the southern edge of CARLINDIE (MGA 737000E 7676300N). This unit is composed of clots of biotite–epidote–titanite–muscovite–actinolite (5% by volume) in a coarse-grained matrix of quartz–plagioclase–K-feldspar (microcline and antiperthite). K-feldspar commonly shows igneous zoning, whereas plagioclase does not. Both feldspars are heavily sausseritized, with local coarse growth of epidote. Some thin sections contain very coarse grained titanite.

A unit of biotite(–hornblende) quartz diorite (*AgLdq*) outcrops in the west-central part of CARLINDIE, where it is well exposed in a number of small, low platforms (e.g. MGA 718250E 7708000N and 719100E 7712200N). This unit is relatively homogeneous and foliated, but generally not migmatitic, although it is locally invaded by voluminous leucogranite sheets of unknown age (Fig. 7). It is commonly a more mafic rock than the tonalitic protoliths of the Wilson Well Gneiss, with a colour index of about 20–25%.

Weakly foliated biotite(–hornblende) leucogranite (*AgLl*) outcrops in scattered parts of CARLINDIE. This rock

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Figure 7. Quarry wall at Carlindie Hill (MGA 718990E 7712260N), showing homogeneous quartz diorite (*AgLdq*; dark phase) cut by voluminous leucogranite sheets

is characterized by 5–8% prisms of black hornblende up to 5 mm long in a medium-grained interlocking assemblage of 35–40% normally zoned plagioclase feldspar (up to 1 cm long), 30% K-feldspar, and 25–30% quartz. The hornblende is commonly altered to biotite–muscovite–epidote (2–3%). The cores of plagioclase crystals are heavily sericitized, with local epidote, whereas the outer, typically untwinned, rims are clear. K-feldspar consists of microperthite and microcline, with local myrmekite, and is typically cloudy with epidote alteration, although many grains still show igneous zonation. Quartz has serrate grain boundaries with feldspars, undulose extinction, and 120° triple-point boundaries with other quartz grains. The rock is unfoliated and only the undulose extinction and subgrain boundary formation in quartz attests to it having been affected by tectonic strain. A sample of this unit (GSWA 153190) has been dated at 3469 ± 2 Ma on NORTH SHAW (Nelson, 1999).

Leucogranite diatexite (*AgLlxn*) is preserved in scattered outcrops throughout the Carlindi Granitoid Complex, but only rarely as areas large enough to be depicted at the scale of mapping. This unit contains more than 50% (more commonly >80%) leucogranite that can be demonstrated to have been derived from melting of tonalitic to monzogranitic orthogneisses (*AgLwi* and *AgLut*) in the same way that diatexite was formed in the Shaw Granitoid Complex (Van Kranendonk, 2000). In these rocks the only layering is defined by wispy biotitic schlieren inherited from the gneissic protolith. Medium-grained homogeneous and schlieric leucogranite (*AgLlr*) is interlayered with patches, lenses, or layers of K-feldspar-rich granite and the mafic mineral content of these rocks is typically less than 2% by volume. Where leucogranite forms approximately 90% or more of the rock, it is mapped as a separate unit, and is commonly homogeneous with only local, faint traces of relict gneissosity.

Salgash Subgroup

On CARLINDIE the Salgash Subgroup of the Warrawoona Group is represented by only the Panorama Formation in the Warralong greenstone belt. The Apex Basalt, which underlies this formation on NORTH SHAW and MARBLE BAR (Hickman, 1983; Van Kranendonk, 2000; Van Kranendonk et al., 2002), is not exposed on CARLINDIE. The Salgash Subgroup forms part of the west-facing, eastern limb of the Warralong Syncline (Fig. 4). Here, the Panorama Formation and Strelley Pool Chert disconformably overlie the Talga Talga Subgroup. Rocks of the Salgash Subgroup are metamorphosed to greenschist facies.

Panorama Formation (AWpsv, AWpfrx, AWpfrt)

Felsic volcaniclastic units of the Panorama Formation reach a maximum thickness of 300 m in the west-facing, eastern limb of the Warralong Syncline. These rocks appear to be conformable on the Towers Formation, and are conformably overlain by quartz-rich sandstone at the base of the Strelley Pool Chert. Felsic volcaniclastic tuff, sandstone, and conglomerate (*AWpsv*) are very similar to their counterparts in the Duffer Formation, being massive to poorly bedded, rich in quartz crystals, and containing sparse altered mica crystals (Fig. 8a,b). Near the top of the formation is coarse rhyolitic breccia (*AWpfrx*) with abundant angular fragments of felsic volcanic material and less common, more rounded, lithic clasts (Fig. 8c), as well as a 20–30 m-thick unit of massive rhyolite. Cutting through the rocks are several thin, black hydrothermal chert veins (too small to show on the map), one of which contains a distinctive pebble-breccia texture of angular to subrounded, silicified host-rock fragments and rounded fragments of black chert (Fig. 8d). A small outcrop of fine-grained, well-bedded rhyolitic tuffaceous sandstone and agglomerate (*AWpfrt*) outcrops along the southern edge of CARLINDIE (MGA 747200E 7676050N).

Kelly Subgroup

Rocks of the Kelly Subgroup (Van Kranendonk et al., 2002) of the Warrawoona Group occupy the central part of the Warralong greenstone belt, and are metamorphosed to greenschist facies. They include the Strelley Pool Chert, the dominantly mafic volcanic rocks and subordinate cherts of the Euro Basalt, and more lithologically diverse rocks of the Wyman Formation. Zircons from a basal unit of felsic tuff in the Euro Basalt, on NORTH SHAW, were dated at c. 3350 ± 2 Ma (Nelson, in prep.b) and are interpreted as giving the age of the onset of volcanism in the Kelly Subgroup. Several dates for the Wyman Formation range between 3325 and 3315 Ma (Thorpe et al., 1992a; McNaughton et al., 1993; Nelson, 2001, 2002; Buick et al., 2002).

Strelley Pool Chert (AWsst, AWsstq, AWsc)

The Strelley Pool Chert lies disconformably on the Panorama Formation on the eastern limb of the Warralong Syncline, and across an erosional unconformity with the Coonterunah Group on the western limb of the Warralong Syncline. The formation consists of a basal unit of felsic tuffaceous sandstone (*AWsst*) and massive, white quartz-rich sandstone (*AWsstq*) and an overlying unit of laminated grey and white chert (*AWsc*). The formation reaches a maximum thickness of up to 520 m along the far-eastern boundary of CARLINDIE (MGA 760000E 7693500N), where it consists largely of quartz-rich sandstone (*AWsstq*) with centimetre- to metre-scale bedding and well-sorted and well-rounded quartz grains to 2 mm.

In general, bedding in the quartz-rich sandstone thins up the stratigraphic section, from metre-thick beds near the base to 50–60 cm-thick beds near the top where cross-bedding is well developed (e.g. MGA 758400E 7692900N), to centimetre- to millimetre-scale bedded sandstones at the top. The quartz-rich sandstone is capped by millimetre- to centimetre-layered grey and white chert (*Awsc*) up to 4 m thick that marks the top of the formation and is interpreted as either silicified laminated mudstones or carbonates. The laminations vary from planar beds to broad wrinkles, but contain no evidence of a clastic texture.

On the western limb of the Warralong Syncline, characteristic wrinkly laminated grey and white chert of

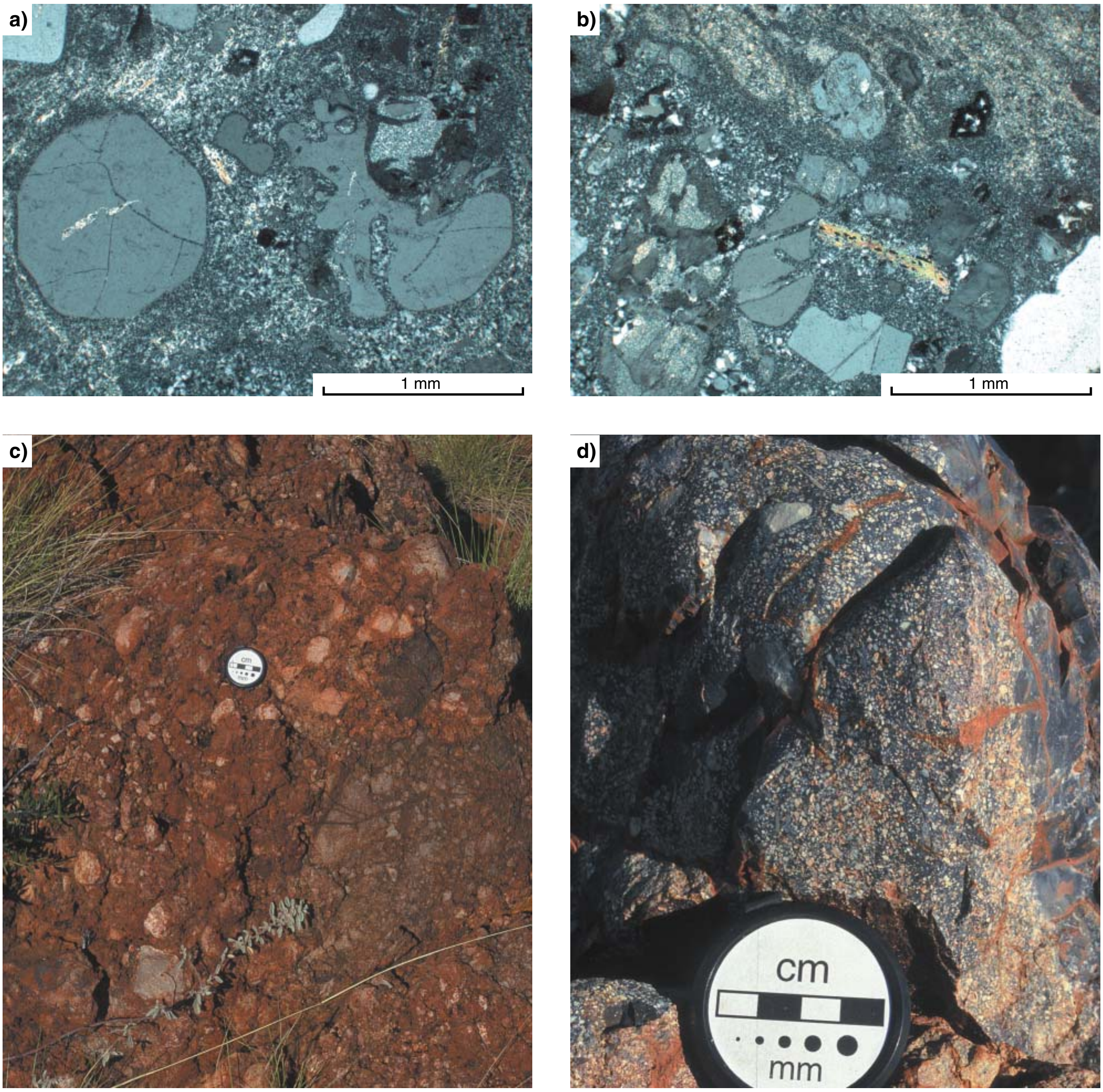

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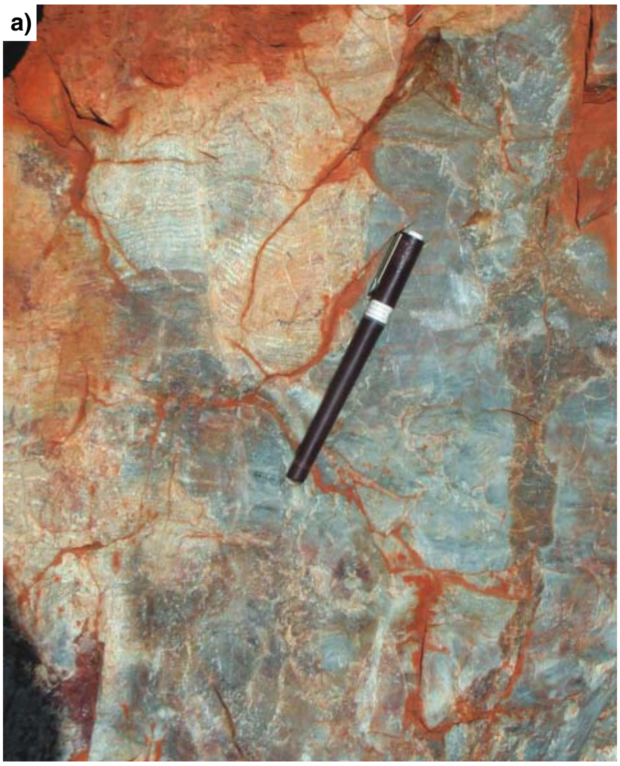
Figure 8. Volcaniclastic sandstone of the Panorama Formation (*AWpsv*): a) photomicrograph, in cross-polarized light, showing euhedral and resorbed quartz crystals in felsic volcaniclastic rock (MGA 758910E 7691375N); b) photomicrograph, in cross-polarized light, showing the several common types of clasts in the volcaniclastic sandstone, including quartz, felsic volcanic rock, and an altered biotite crystal in a matrix of fine- to medium-grained recrystallized quartz (MGA 758910E 7691375N); c) felsic volcanic breccia near the top of the formation (*AWpfrx*; MGA 758800E 7694000N); d) hydrothermal silica vein packed with clasts of silicified fragments of host felsic volcanic rocks (MGA 758800E 7694000N)

the Strelley Pool Chert (*AWsc*; Fig. 9a) reaches up to 4 m in thickness (MGA 749750E 7689250N) and overlies up to 20 m of cobble to boulder conglomerate (Fig. 9b) and sandstone (*AWsst*; Fig. 9c) derived from the immediately underlying felsic volcanic rocks of the Coonterunah Group. The chert is commonly brecciated and deformed in this area and varies to milky white massive chert along strike to the northeast. The underlying conglomerate consists mainly of angular to rounded clasts of chert-veined, feldspar-porphyritic rhyodacite in a matrix of medium-grained feldspathic sandstone, and fines upward to sandstone and fine-grained sandstone and siltstone.

A sample (GSWA 142836) of quartz-rich sandstone of this formation (*AWsstq*), from just east of Carlindie on Coongan, returned detrital zircon populations with ages of 3426 ± 10 Ma (7 zircons) and 3602 ± 5 Ma (24 zircons), the former providing a rough indication of the maximum age of deposition of the sediment (Table 2; Nelson, 1998).



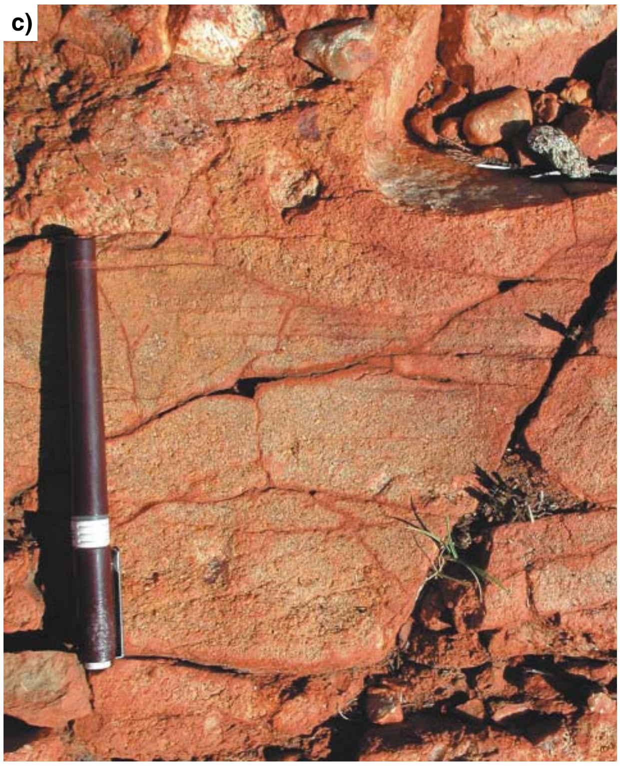


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Figure 9. The Strelley Pool Chert on the western limb of the Warralong Syncline (MGA 749700E 7689200N): a) characteristic grey and white, millimetre-laminated chert (*AWsc*); b) underlying coarse conglomerate consisting of angular to rounded boulders to cobbles of feldspar-porphyritic rhyodacite of the underlying Coonterunah Group; c) horizontal outcrop surface of 30 cm-thick sand bed with basal scour indicating way up towards top of photograph, which is southeast

Euro Basalt (AWeb, AWebk, AWebs, AWed, AWebc, AWebks, AWeft, AWecc, AWeccw, AWecch, AWest, AWestq)

The Euro Basalt lies conformably on the Strelley Pool Chert and is unconformably overlain by either the Sulphur Springs Group (MGA 750700E 7688150N) or Gorge Creek Group (MGA 757700E 7690400N), reaching a maximum thickness of about 3000 m on the western limb of the Warralong greenstone belt and in the western part of the Panorama greenstone belt.

On CARLINDIE the Euro Basalt consists dominantly of pillowed basalt flows with subordinate interflow cherty sedimentary rocks and minor felsic tuffs. Steeply dipping, north-facing pillowed tholeiitic basalt (*AWeb*) and interbedded komatiitic basalt (*AWebk*) are the dominant components of the Panorama greenstone belt, with subordinate interflow sedimentary rocks described below. Basaltic rocks of uncertain composition (*AWebs*) were mapped along the sheared eastern margin of the syncline (MGA 753500E 7689500N). Subvolcanic feeder dykes to tholeiitic pillow basalts (*AWed*) cut through the basalts in the Panorama greenstone belt in the area of an eruptive vent on NORTH SHAW (Van Kranendonk, 1998, 2000).

Pillowed komatiitic basalts (*AWebk*) on the eastern limb of the Warralong Syncline are overturned, whereas those on the western limb of the fold dip steeply, but are right way up and face east. Folded pillow forms help define the axial trace of the Warralong Syncline just east of the track in the central part of the greenstone belt (MGA 754800E 7690600N). Pillows are up to 2 m in diameter and contain pillow shelves, gas cavities, amygdales, ocelli, marginal pipe vesicles, bleached alteration margins, and interpillow hyaloclastite. Pillow basalt (*Aweb*) overlies the Strelley Pool Chert both on the western limb of the Warralong greenstone belt (~2500 m thick) and in the northern part of the Panorama greenstone belt along the southern boundary of CARLINDIE in the North Pole Dome (~2000 m thick).

Metamorphosed and carbonate-altered pillowed basalts (*AWebc*) with locally well preserved igneous textures outcrop on the northwestern limb of the Warralong Syncline and weather to a distinctive dark-brown colour. Strongly sheared chlorite–carbonate schists derived from komatiitic basalt protoliths (*AWebks*) occupy the core of the syncline.

Interbedded with the basaltic volcanic rocks are thin interflow sedimentary units, including felsic tuff, chert, and clastic sedimentary rocks. A 50 m-thick unit of finely bedded, very fine grained felsic ash (*AWeft*) on the eastern limb of the Warralong Syncline (MGA 756400E 7691500N) was sampled for U–Pb zircon dating, but returned only ages of the Fortescue Group (Nelson, D. R., written comm., 2002), indicating that the grains are recrystallized or hydrothermal. Cherty metasedimentary rocks include more common, layered to massive, white, grey, and blue-black units (*AWecc*) and less common units of centimetre-layered white and grey chert (*AWeccw*). Some bedded cherts are continuous with massive blue-black hydrothermal silica veins (*AWecch*; MGA 749000E 7677000N) a few metres wide by several tens of metres long that cut through the footwall volcanic rocks, but do not extend above the bedded cherts.

Units of clastic sedimentary rocks are interbedded with pillow basalts in the core of the Warralong Syncline. These include medium-grained, bedded to massive quartz-rich sandstones (*AWestq*) and grey-weathering, fine-grained sandstone that locally preserve flute casts, with local quartz-rich sandstone, granule conglomerate, and layered blue-black and grey chert (*AWest*). In one area (MGA 754500E 7692000N), coarse sandstone to granule conglomerate of this unit, with angular (<4 cm) to rounded (~1 cm) clasts of black chert and quartz in a silica-cemented matrix, is cut by and interlayered with an irregular network of massive grey hydrothermal silica veins, suggesting an intimate inter-relationship between hydrothermal veining, erosion, and redeposition.

Wyman Formation (AWwstq, AWwcch, AWwb, AWwft, AWwsp)

Rocks of the Wyman Formation outcrop in the central part of the Warralong greenstone belt, where they unconformably overlie the Euro Basalt (Fig. 10) and reach a maximum preserved thickness of about 1750 m. The general stratigraphy consists of a basal unit of chert-rich and quartz-rich sandstone that is overlain by basalt with thin units of chert, grey tuffaceous siltstone and chert, quartz-rich sandstone, and minor felsic volcaniclastic rocks.

The stratigraphically lowest part of the Wyman Formation is a 50–400 m-thick unit of quartz-rich sandstone (*AWwstq*) that includes minor pebbly sandstone to granule conglomerate with chert clasts and minor felsic volcaniclastic rock (<25 m thick). This unit overlies a swarm of 1–10 m-thick, blue-black hydrothermal chert veins (*AWwcch*) that are spatially associated with intense carbonate alteration of the footwall Euro Basalt (Fig. 10). The thickest part of the sandstone fills an incised channel in the Euro Basalt in an area replete with black hydrothermal chert veins (Fig. 10). At the base of the formation is a discontinuous, 5–10 m thick unit (too small to show on the main map) of coarse-grained (clasts to 5 cm) angular conglomerate with or without breccia that is composed of black chert fragments in a sandy matrix. Overlying the conglomerate is a blue-grey sandstone with sand- to pebble-sized clasts of grey to dark-blue chert in a coarse quartz – chert sand matrix with a silica cement (Fig. 11). A sample of this unit (GSWA 168992 on Fig. 10) contained detrital zircon populations dated by U–Pb SHRIMP geochronology at 3324 ± 4 and 3603 ± 5 Ma (Table 2; Nelson, 2002). Higher up, a sample of pure-white quartz-rich sandstone with poorly defined bedding and quartz sand grains to 2 mm in diameter (GSWA 168993 on Fig. 10) contained a single population of detrital zircons at 3508 ± 3 Ma (Nelson, 2002). Along strike to the east, the basal part of the sandstone unit includes up to 20 m of fine-grained felsic volcaniclastic rock (Fig. 10). Farther east still, the overlying lithology includes brown-weathering sandstone with cross-beds in bedsets 30 cm thick in addition to bedded grey chert and quartz-rich sandstone.

Neptunian dykes of sandstone were observed in some of the massive black-chert veins, and an erosional contact between the sandstone and the chert veins was mapped in some areas (Fig. 10 inset). However, sills of black chert were also observed in the sandstone, suggesting a partly contemporaneous relationship between sandstone deposition and chert veining, supported by the monomict nature of the chert granule conglomerate. Map data also show that sandstone deposition was contemporaneous with faulting, as evidenced by the change in stratigraphic thickness of the unit across north–south faults (Fig. 10).

Lying above the basal sandstone unit across an unexposed contact is up to 1000 m of undivided basalt (*AWwb*). The basalt is typically carbonatized. Well-preserved pillows were observed at one locality (MGA 751350E 7689000N). Within the upper part of the basalt is a thin unit of quartz-rich sandstone (*AWwstq*) interbedded with a grey to yellow-grey weathering unit (up to 6 m thick) of fine-grained ?felsic volcaniclastic siltstone (*AWwft*) that is interbedded with silicified fine-grained volcaniclastic rocks and thin beds of grey sandstone and quartz-rich sandstone (up to 12 m thick; *AWwsp*). These rocks are intruded by vein silica and barite. The area where these rocks are exposed (MGA 751300E 7688350N) is very complexly deformed, although bedding in individual dismembered and folded panels of competent, silicified clastic rocks is well preserved.

Carlindi Granitoid Complex (*AgLmh*)

A unit of homogeneous, strongly foliated and folded hornblende monzogranite (*AgLmh*) outcrops in the Strelley

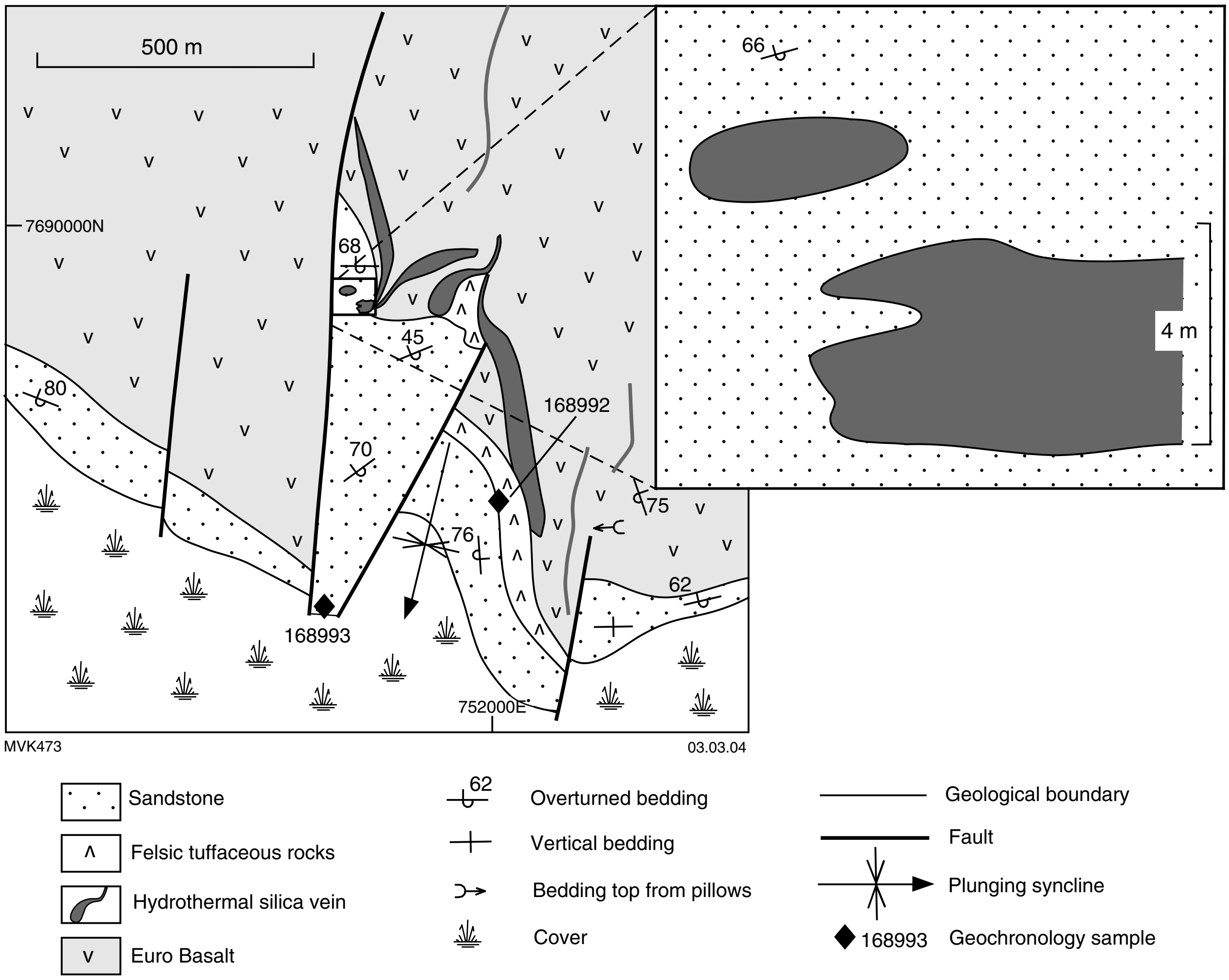

Figure 10. Geological sketch map of the basal contact of the Wyman Formation in the central part of the Warralong greenstone belt. Note the disconformable nature of the contact with the Euro Basalt, as indicated by a high angle of bedding discordance to the lower right. Note also the apparent synkinematic nature of sandstone deposition with faulting, as indicated by thickness changes in sandstone across faults (locality centred at MGA 751800E 7689300N)

River East in the central part of Carlindie (MGA 734600E 7698100N). The monzogranite is mesocratic and monocyclic, varying from weakly foliated to strongly foliated. In places it contains schlieric to gneissic tonalite enclaves of the Wilson Well Gneiss (*AgLwi*) that are aligned parallel to the main foliation in the host rock. Both the gneissic inclusions and the main foliation in the host rock are folded on upright axial planes (Fig. 12; see **Structural geology of the northern part of the Pilbara Craton**).

Compositions vary from hornblende monzodiorite to hornblende monzogranite. The igneous hornblende is retrogressed to epidote–chlorite and minor titanite, and plagioclase is altered to sericite and epidote. Epidote forms wide rims on coarse monazite crystals, and thin sections reveal trace zircon and apatite. Myrmekite textures are common at margins of K-feldspar crystals. Deformation has caused the recrystallization of many igneous crystals into subgrains along their boundaries. A sample of this unit (GSWA 178040) has returned a U–Pb zircon SHRIMP age of 3252 ± 4 Ma (Table 2; Nelson, in prep.b).

Sulphur Springs Group

Rocks belonging to the Sulphur Springs Group outcrop in the southwestern part of the Warralong greenstone belt, in the hinge region of the Warralong Syncline where they lie with angular unconformity on rocks of the Warrawoona Group (Figs 13 to 15). The group reaches a maximum thickness of about 2400 m along the axial hinge of the Warralong Syncline and is conformably overlain by quartz-rich sandstones of the Gorge Creek Group. The rocks are metamorphosed at lower greenschist facies, with generally excellent preservation of original sedimentary and igneous textures.

Leilira Formation (*ASlstq*)

The basal Leilira Formation of the Sulphur Springs Group (Van Kranendonk et al., 2002) on Carlindie is composed predominantly of white to grey, medium- to coarse-grained quartz-rich sandstone with hydrothermal quartz and barite

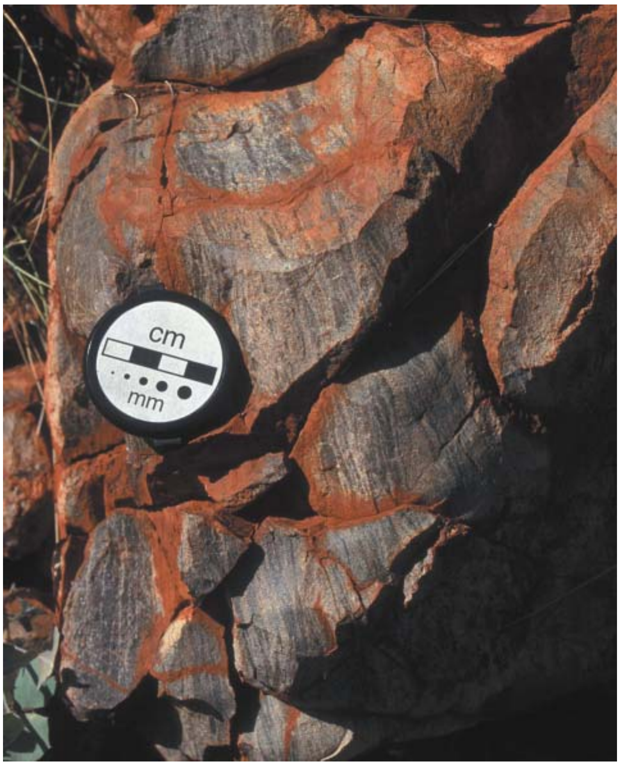

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Figure 11. Chert-pebble sandstone at the base of the Wyman Formation (GSWA 168992, MGA 749980E 7689420N)

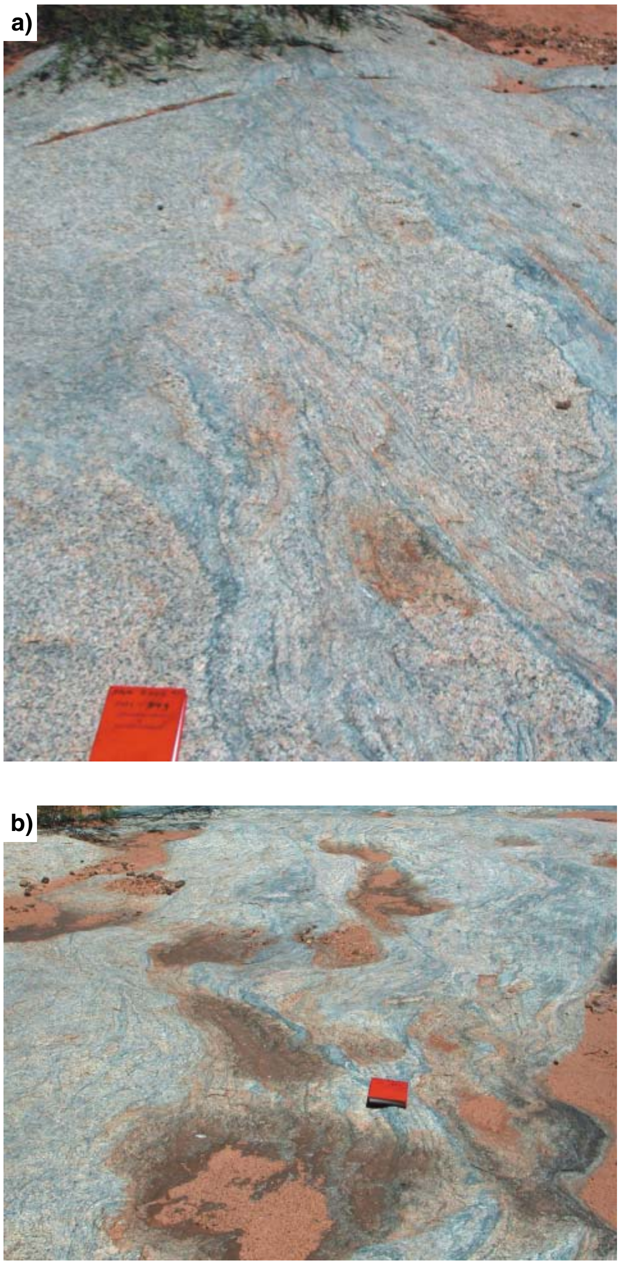

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Figure 12. a) Folded, migmatitic tonalitic orthogneiss (*AgLwi*) in hornblende monzogranite (*AgLmh*; under notebook); b) outcrop view to east-northeast of migmatitic tonalitic orthogneiss enclave in foliated monzogranite (*AgLmh*), showing east-striking migmatitic gneissosity deformed by open to closed F_3 folds (both photos from MGA 734600E 7698400N)

cement (*ASlstq*) that reaches a maximum thickness of about 20 m in local scours, but is discontinuous along strike. Locally, there is a discontinuous basal conglomerate up to 1.5 m thick in this unit, with angular fragments, up to 10 cm across, of layered black and grey chert (Fig. 16a). Rocks of the basal unit are cut by grey to milky white chert veins and thick barite veins. The matrix of the rock is composed of fine-grained (cherty) quartz that forms spherulites (Fig. 16b), indicating recrystallization of matrix material from hot, siliceous (hydrothermal) fluids. Barite has also been identified in the matrix of these sandstones (Hickman, 1977b). The formation includes a laterally discontinuous layered unit (e.g. MGA 752750E 7698100N) comprising couplets of dark-brown-weathering carbonate and green-grey chert, millimetres to metres thick.

Kunagunarrina Formation (*ASkbk*, *ASkslv*, *ASkstq*, *ASksw*, *ASksh*, *ASksc*, *ASkcc*)

The Kunagunarrina Formation is up to 1200 m thick in the core of the Warralong Syncline, but the formation thins on the fold limbs to about 300 m. At the base of the formation, overlying the quartz-rich sandstones of the Leilira Formation, are very fine grained and thinly bedded, grey mudstone (silicified ash), centimetre-layered grey cherts (silicified tuffaceous siltstones), and carbonate-altered tuffaceous sandstones. These rocks form a discontinuous unit up to a maximum thickness of a few metres and are too small to show on the map; their composition is unknown, but they are interpreted to represent volcaniclastic material derived from komatiitic basalt. In the eastern part of the hinge of the Warralong Syncline, a pale-yellow-weathering unit of what appears to be a highly vesicular, flow-banded rhyolite overlies the basal quartz-rich sandstone of the Leilira Formation.

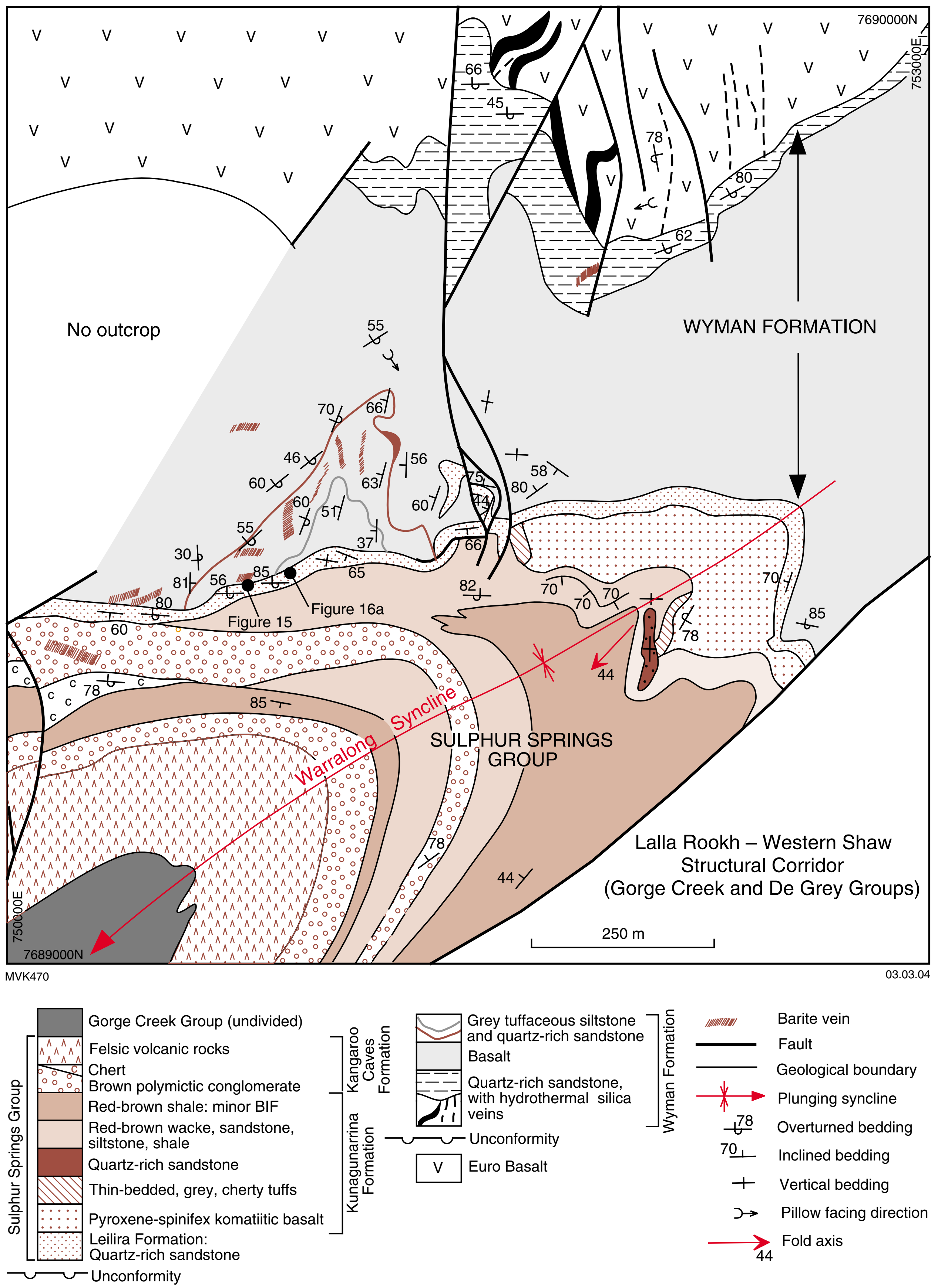

Figure 13. Geological sketch map showing the unconformable relationship of the Sulphur Springs Group on the Wyman Formation of the Warrawoona Group (locality centred at MGA 751600E 7688350N)

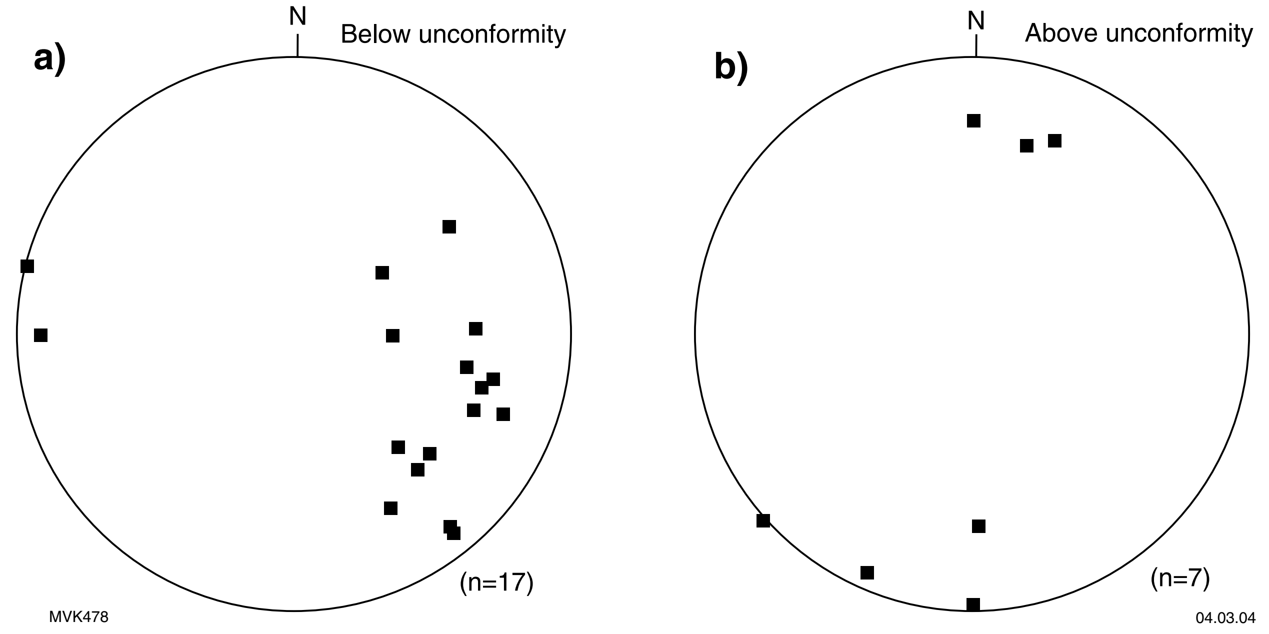

Figure 14. a) Equal area stereoplots of poles to bedding from the Wyman Formation of the Warrawoona Group from beneath the unconformity (n=17); b) equal area stereoplot of poles to bedding from the basal quartz-rich sandstone of the Sulphur Springs Group above the unconformity (n=7)

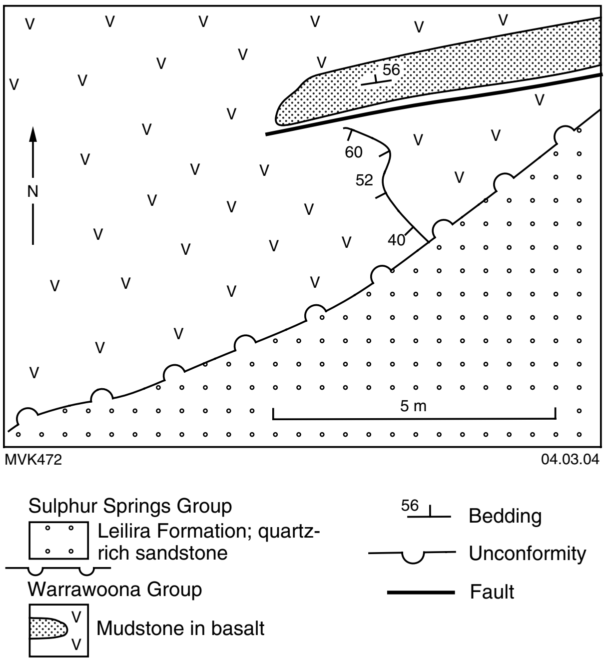

Figure 15. Detailed geological sketch map of the unconformity at the base of the Sulphur Springs Group, showing folded and faulted mudstone of the Wyman Formation (Warrawoona Group) unconformably overlain by quartz-rich sandstone of the Leilira Formation (Sulphur Springs Group; see Fig. 13 for location)

However, thin section petrography reveals that this unit is a silicified komatiitic basalt with relict micropyroxene-spinifex texture and altered amygdales or ocelli (*ASkbk*; Fig. 17). The base of this unit is fairly massive, but the top contains lobe-like structures, with some hyaloclastite. They are overlain by a thin ridge of silicified, millimetre-bedded, grey, tuffaceous mudstones and siltstones (*ASkslv*).

Up to 600 m of clastic sedimentary rocks disconformably overlies the lower komatiitic basalts and tuffaceous rocks, and have cut down through these rocks progressively from east to west across the hinge of the Warralong Syncline (Fig. 13). A discontinuous, northerly striking ridge of quartz-rich sandstone (*ASkstq*), 500 m long and less than 5 m wide, lies with erosional disconformity on grey mudstone and millimetre-bedded ash tuff of the Kunagunarrina Formation (*ASkslv*) on the eastern limb of the fold (MGA 752250E 7688100N; Fig. 13). This quartz-rich sandstone ridge is truncated to the north by fine-grained reddish-brown-weathering wacke, sandstone, and shale (*ASksw*), which grades up into red-brown-weathering shale (*ASksh*) with thin (<1 m) layers of black, red, and white banded iron-formation that forms a thick unit in the hinge region of the fold. Overlying the shale is another unit of wacke and sandstone, then dark-brown-weathering, polymictic pebble to cobble conglomerate (*ASksc*) that has dominantly well rounded pebbles of grey-white, fine-grained, altered pyroxene-spinifex textured komatiitic basalt (Fig. 18a,b) and subordinate amounts of other clasts including black chert, and quartz-rich sandstone (Fig. 18c,d). The conglomerate is locally massive, but fines upward overall to well-bedded sandstone and siltstone. In thin section the conglomerate contains clear volcanic quartz sand grains set in a fine-grained matrix of quartz

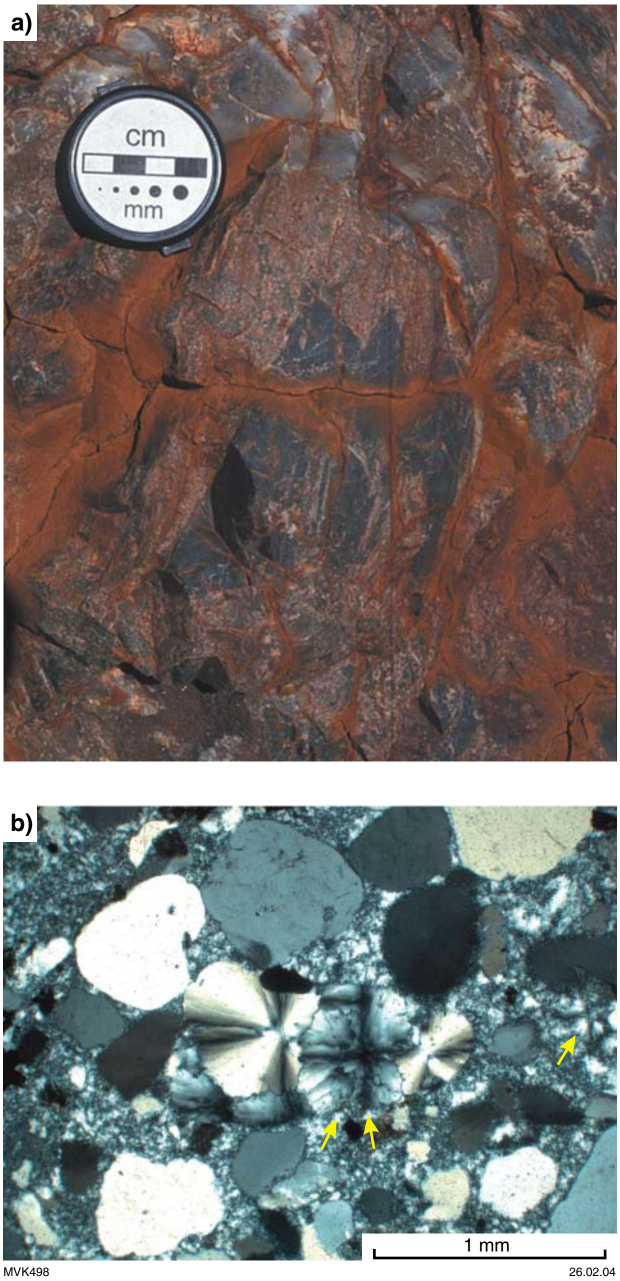

Figure 16. Features of the quartz-rich sandstone (*ASlstq*) at the unconformity at the base of the Sulphur Springs Group on the Warrawoona Group: a) angular chert cobbles in quartz-rich sandstone matrix (see Fig. 13 for location); b) cross-polarized light thin section view of quartz-rich sandstone, showing spherulites of radiating quartz fibres in the silicified matrix of the rock, between sand grains of clear volcanic quartz (MGA 749500E 7687700N)

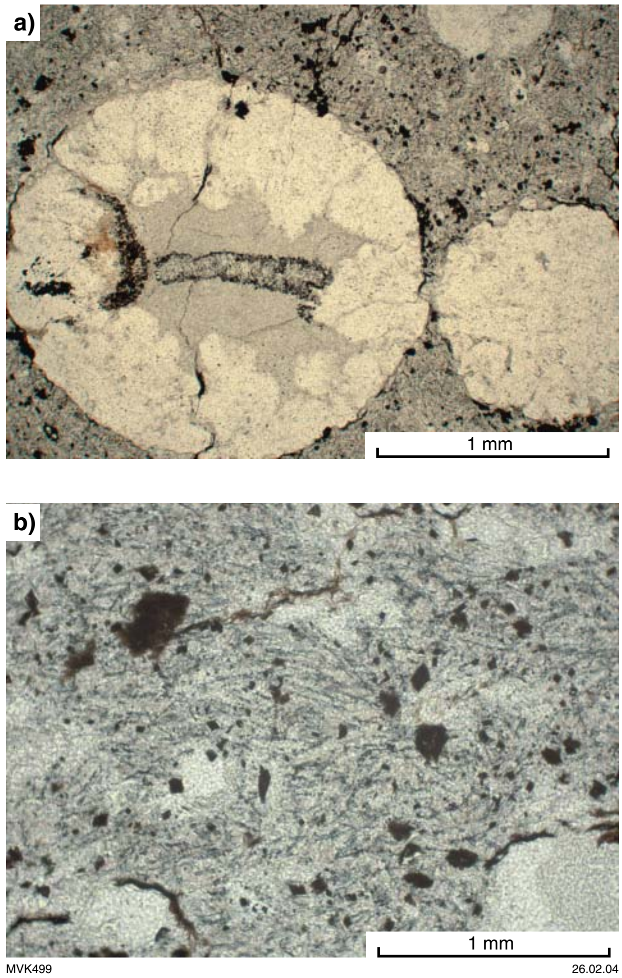

Figure 17. Altered basaltic komatiite of the Kunagunarrina Formation (*ASkbk*; MGA 752500E 7688100N): a) plane-polarized light view of amygdales or ocelli replaced by carbonate in fine-grained matrix; b) plane-polarized light view of volcanic groundmass, showing faint pyroxene-spinifex texture

and carbonate (Fig. 18d,e). Within the conglomerate are 1–3 m-thick beds of dark-brown-weathering, massive or pillowed mafic–ultramafic units, indicating intermittent, contemporaneous volcanism during conglomerate deposition. It is primarily for this reason that the underlying sedimentary rocks are assigned to the Kunagunarrina Formation.

The conglomerate unit is locally (MGA 750300E 7687900N) overlain by less than 100 m of millimetre-bedded dark blue-black to grey layered chert (*ASkcc*), probably representing silicified siltstone–shale, overlain by grey-brown shale.

Kangaroo Caves Formation (*AScsc*, *AScsv*)

The Kangaroo Caves Formation of the Sulphur Springs Group reaches a maximum thickness of 800 m in the hinge of the Warralong Syncline on CARLINDIE. The exposure of the contact between the Kangaroo Caves Formation and the underlying Kunagunarrina Formation (MGA 749700E 7687800N) is an erosional disconformity between quartz-rich coarse sandstone above and centimetre- to millimetre-bedded ?tuffaceous siltstone below (Fig. 19). A low-angle disconformity between millimetre-bedded grey chert and pebble conglomerate was also noted farther west (MGA 748500E 7687100N).

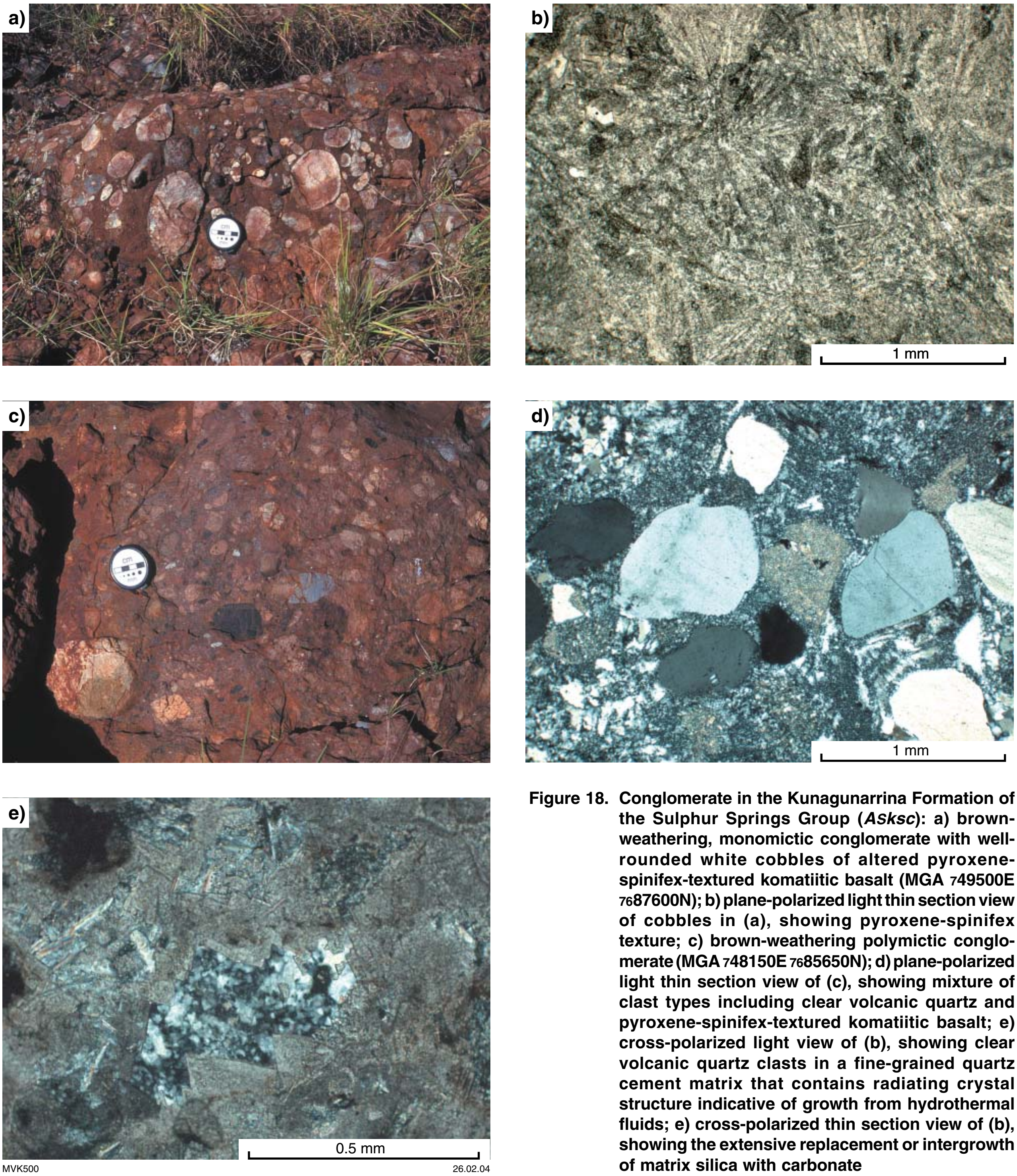

Figure 18. Conglomerate in the Kunagunarrina Formation of the Sulphur Springs Group (*ASksc*): a) brown-weathering, monomictic conglomerate with well-rounded white cobbles of altered pyroxene-spinifex-textured komatiitic basalt (MGA 749500E 7687600N); b) plane-polarized light thin section view of cobbles in (a), showing pyroxene-spinifex texture; c) brown-weathering polymictic conglomerate (MGA 748150E 7685650N); d) plane-polarized light thin section view of (c), showing mixture of clast types including clear volcanic quartz and pyroxene-spinifex-textured komatiitic basalt; e) cross-polarized light view of (b), showing clear volcanic quartz clasts in a fine-grained quartz cement matrix that contains radiating crystal structure indicative of growth from hydrothermal fluids; e) cross-polarized thin section view of (b), showing the extensive replacement or intergrowth of matrix silica with carbonate

The sandstone grades upward over a short distance to an orange-weathering, polymictic, matrix-supported pebble to cobble conglomerate (*AScsc*) with clasts of altered volcanic rocks, sandstone, felsite, and chert in a sand-sized matrix rich in quartz (Fig. 20a). Thin sections of the conglomerate show that it contains clasts of altered komatiitic basalt (Fig. 20b,c), but is distinct from the underlying conglomerate (*ASksc*) because it contains numerous shards of devitrified felsic volcanic glass (Fig. 20c,d). The conglomerate grades up into sandstone, and quartz-rich sandstone interbedded with up to 15 m of red-weathering shale in the hinge of the Warralong Syncline.

These rocks are overlain by up to 600 m of yellow-orange-weathering, felsic volcaniclastic sandstone that is typically massive and lacks discernible bedding (*AScsv*) at its base, where it contains clear quartz and feldspar phenocrysts to 8 mm and sparse clasts of chert to 2 cm. In thin section (Fig. 21) this unit contains angular to sub-rounded volcanic quartz crystal fragments (60% by volume), lithic fragments (35% by volume) consisting of

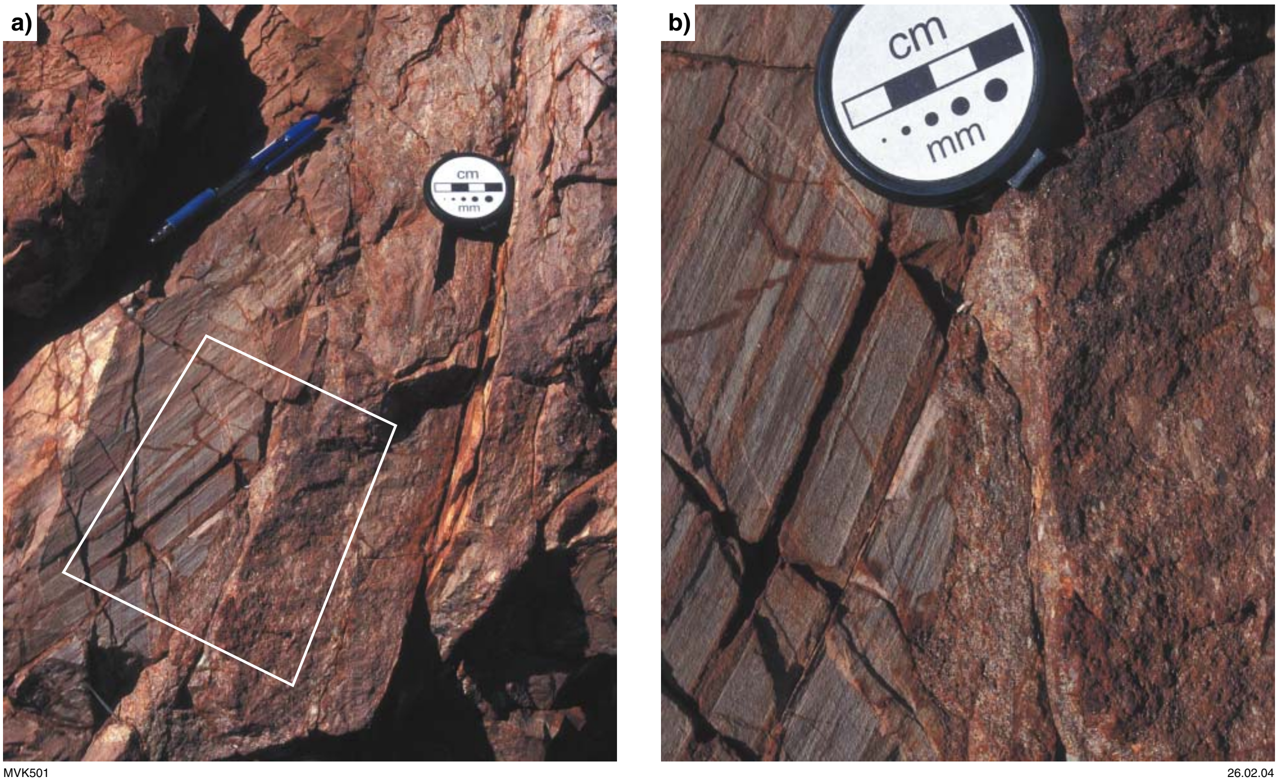

Figure 19. a) The overturned unconformity between the Kunagunarrina Formation (fine-grained, well-bedded tuffaceous siltstone to left) and the Kangaroo Caves Formation (quartz-rich sandstone at right). Location of (b) indicated by rectangle (MGA 749615E 7687700N); b) close-up of (a), showing the erosional nature of the overlying sandstone on siltstone

fine-grained sericite–quartz–carbonate, and altered biotite crystal fragments (3–4% by volume) with trace apatite and zircon. Lithic clasts include chert, altered felsic volcanic rocks, and altered komatiitic basalt. Passing upward through the unit, bedding is still poorly developed, but there are metre-scale beds with rounded cobbles up to 20 cm indicating that the unit is a polymictic (though largely felsic) volcaniclastic conglomerate, possibly an epiclastic debris flow. The coarser grained top of the unit contains angular felsic volcanic fragments.

Gorge Creek Group

Rocks of the Gorge Creek Group outcrop on either side of the Lalla Rookh Synclinorium in the Warralong greenstone belt (Corboy and Paddy Market Formations) in the southeastern part of CARLINDIE, and in the Tabba Tabba Shear Zone (Cleaverville Formation) in the northwestern corner of CARLINDIE (Figs 3 and 4).

The Gorge Creek Group reaches a maximum thickness of about 1400 m along the eastern margin of CARLINDIE on the northern limb of the Lalla Rookh Synclinorium. In the Warralong greenstone belt the group lies unconformably on the Warrawoona Group and with apparent conformity on the Sulphur Springs Group. It is unconformably overlain by the De Grey and Fortescue Groups.

Corboy Formation (*AGcsc*, *AGcstq*)

The Corboy Formation is well exposed in the Warralong greenstone belt where it reaches a maximum stratigraphic thickness of about 1250 m at the eastern edge of CARLINDIE (MGA 759750E 7692000N). It forms the basal unit of the group in this area, and consists of a discontinuous basal unit of polymictic boulder to pebble conglomerate (*AGcsc*; Fig. 22a), up to 50 m thick, and an overlying unit of quartzite (*AGcstq*) that varies from 100 to 1100 m in thickness. The formation lies on a variety of older rocks across a contact that changes in character from west to east. In the west the unit lies conformably on rocks of the Sulphur Springs Group (*AScsv*; MGA 750000E 7687200N), whereas in the east it overlies pillow basalts (*AWebk*) and felsic tuffaceous rocks (*AWeft*) of the Euro Basalt across an high-angle (90°) angular unconformity (MGA 756100E, 7696200N). The quartz-rich sandstone is conformably overlain by banded iron-formation and shale of the Paddy Market Formation (*AGpci*).

The basal polymictic conglomerate of the formation (*AGcsc*) contains a variety of clasts, up to 60 cm in diameter, which are well rounded to angular, the latter commonly with internal fractures (Fig. 22a). Clast types include common quartzite, centimetre-bedded grey and white chert, jaspilitic cherty banded iron-formation,

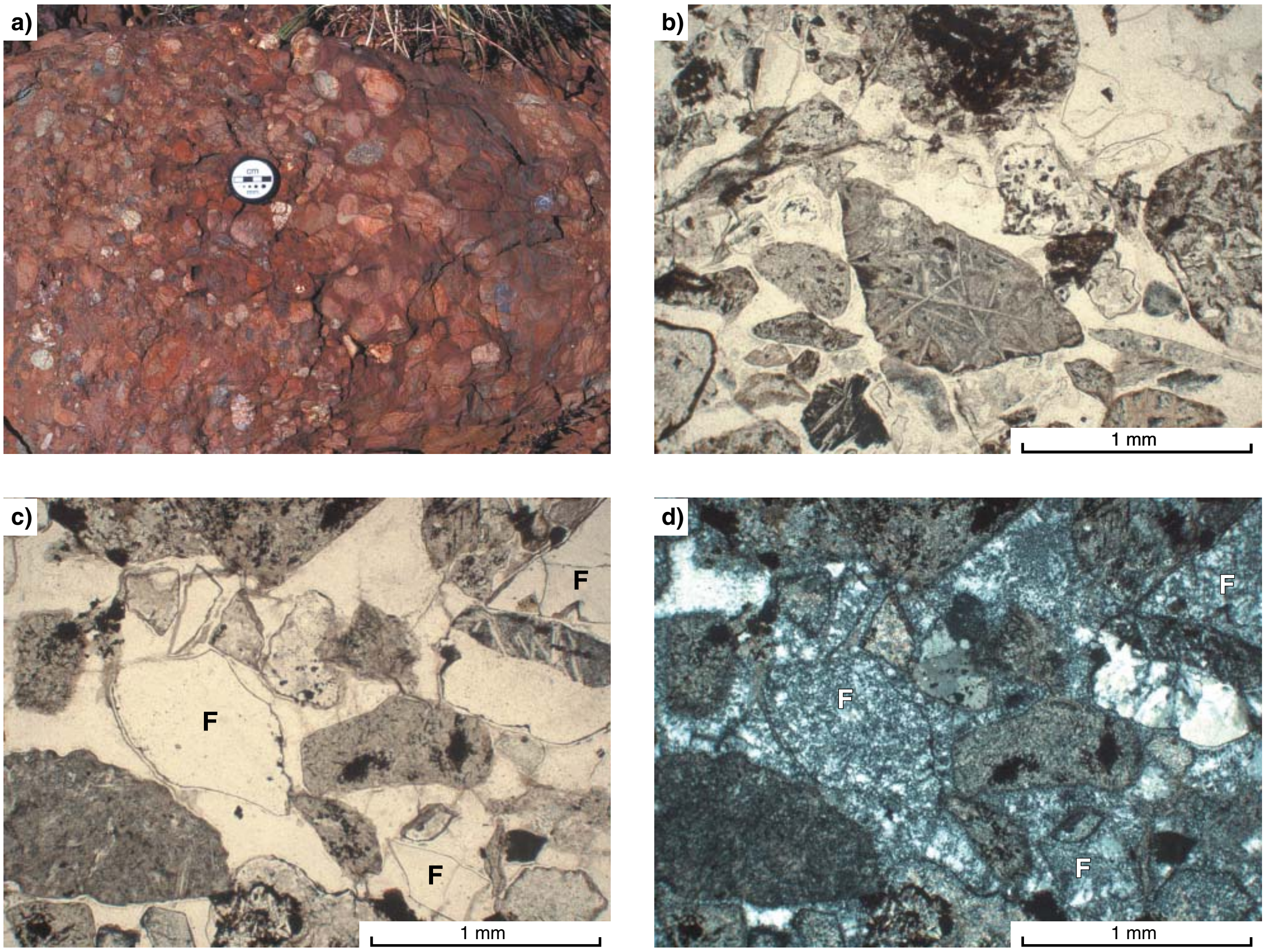

Figure 20. Basal conglomerate of the Kangaroo Caves Formation (*AScsc*): a) outcrop view of polymictic conglomerate (MGA 749600E 7687600N); b) and c) plane-polarized light thin section views of polymictic conglomerate, showing mixture of pyroxene-spinifex-textured komatiitic basalt and devitrified felsic volcanic glass shard clasts (MGA 749500E 7687450N); d) cross-polarized light thin section view of (c); note the devitrified felsic volcanic glass shards (F) and the clast with quartz spherulites

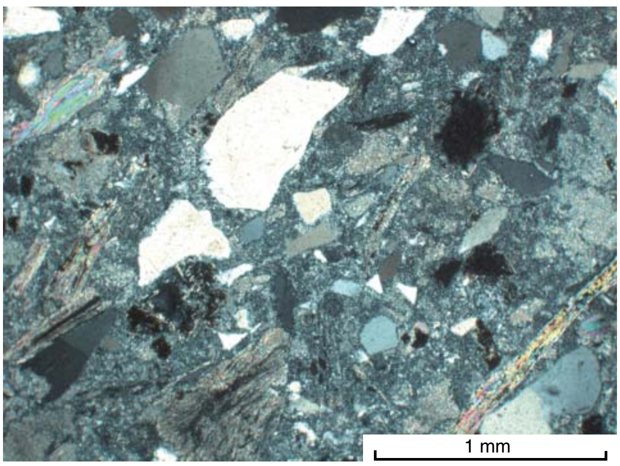

Figure 21. Volcaniclastic sandstone of the Kangaroo Caves Formation (cross-polarized light). Note the angular quartz-crystal fragments, lithic clasts, and altered biotite fragments (MGA 749400E 7687380N)

and one boulder of silicified breccia (fault or hydrothermal breccia). Bedding is poorly developed in this unit, although local 1 m-thick sandy beds were observed towards the top of the unit, consisting of coarsening- and fining-upward sequences, and local flame structures (Fig. 22b). Farther east, on COONGAN, the basal conglomerate contains clasts of white vein quartz, volcanic rocks, and green chert in addition to those described above.

Quartz arenite and quartz-rich sandstone (*AGcstq*) form the bulk of the Corboy Formation on CARLINDIE and are thickly bedded and very pure. Most original bedding features have been obscured by mild to strong silicification, attributed to ?Cainozoic weathering, although cross-bedding is locally preserved. This unit is characteristically bright white in colour and remarkably homogeneous, although there are local beds with chert pebbles. A sample of this quartzite (GSWA 168997), from about 2 km east of the map sheet on COONGAN (Van Kranendonk, 2004), yielded detrital zircons as young as 3410 ± 6 Ma (Nelson, 2002; see **Geochronology** and Table 2).

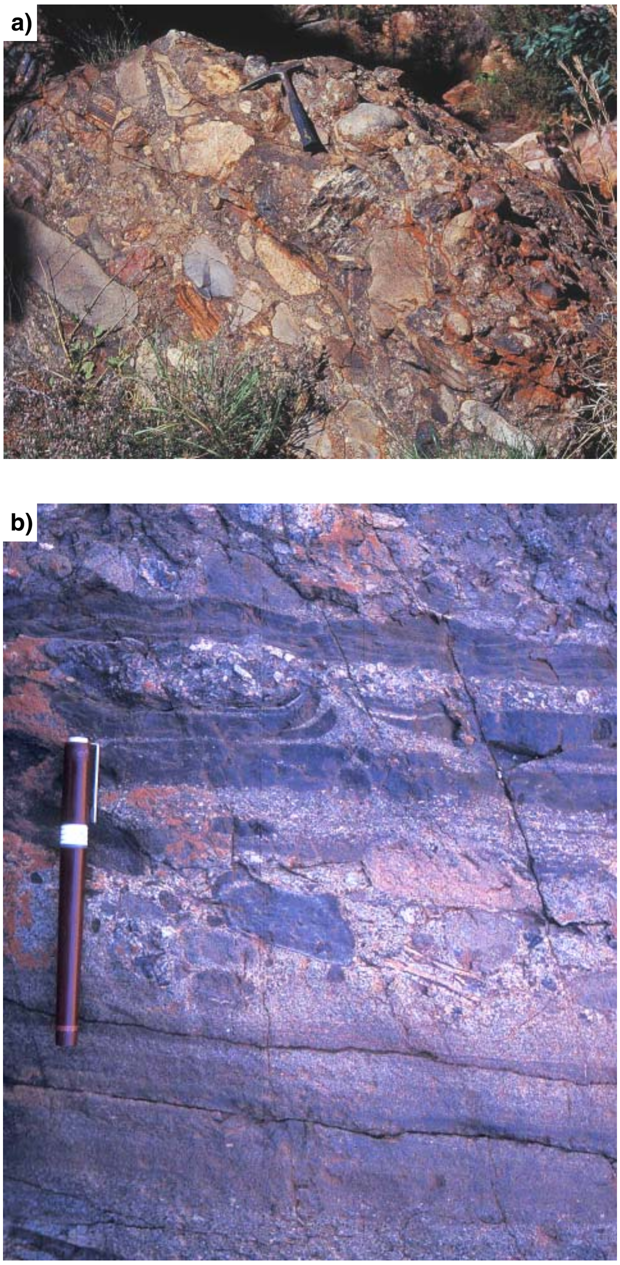

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Figure 22. a) Polymictic boulder conglomerate at the base of the Corboy Formation of the Gorge Creek Group (<3235 Ma), which lies across an angular unconformity with the underlying, c. 3350–3325 Ma Euro Basalt of the Warrawoona Group (MGA 755640E 7690200N); b) Graded conglomerate–sandstone–mudstone beds from near the top of the basal polymictic conglomerate of the Corboy Formation, Gorge Creek Group (*AGcsc*; MGA 755700E 7690250N))

Paddy Market Formation (*AGpci*, *AGpsh*, *AGpstq*, *AGpshz*)

Rocks of the Paddy Market Formation outcrop in both the Warralong and Panorama greenstone belts. In the former belt the formation is about 500 m thick, conformably overlies the Corboy Formation of the Gorge Creek Group, and is unconformably overlain by the Lalla Rookh Sandstone of the De Grey Group (*ADlst*). In the latter belt the contact of the formation with the Euro Basalt is not exposed, but is interpreted to be a fault.

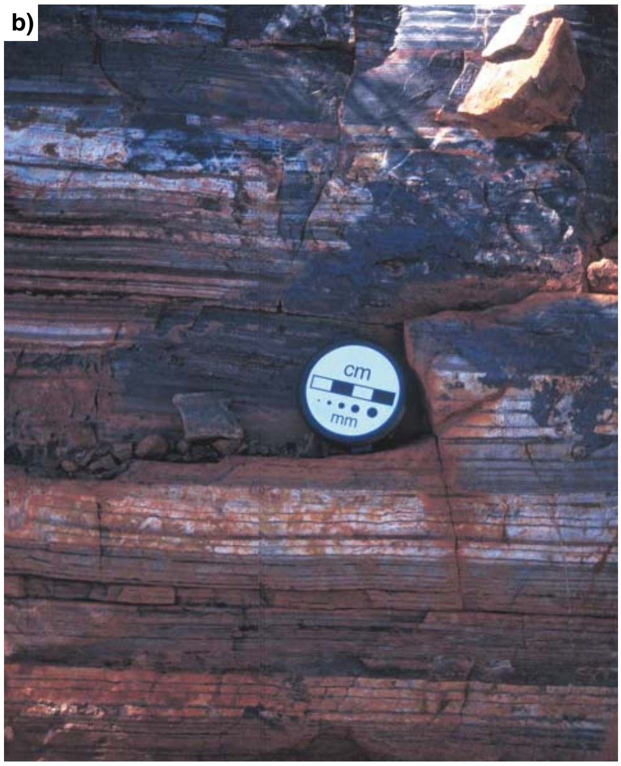
In the Warralong greenstone belt the Paddy Market Formation locally consists of a basal unit of grey mudstone and grey- to red-weathering shale (<100 m thick, not shown on map) that passes up into thinly bedded, black, white, red, and grey layered cherty banded iron-formation (*AGpci*), which forms the dominant component of the formation (Fig. 23a). The banded iron-formation is composed of millimetre-scale laminations of hematite and magnetite that are grouped into centimetre-scale layers. Common limonite layers are the result of weathered primary mineralogy. In the southwestern part of the belt (MGA 747400E 7682350N), red and grey shale (*AGpsh*) outcrops over large areas, and contains black and white layered, cherty, banded iron-formation interbeds up to several metres thick. In this area the shales and banded iron-formation both overlie and underlie a 50–200 m-thick unit of white to grey quartz-rich sandstone with pebbly conglomerate interbeds (*AGpstq*).

On the southern limb of the Lalla Rookh Synclinorium, the Paddy Market Formation consists predominantly of grey and white layered chert (Fig. 23b) that represents an originally fine-grained clastic sedimentary rock (shale and possible tuff) that has been pervasively silicified by a network of dark-grey silica veins (*AGpshz*). A 30 cm-thick bed near the base of the formation in this area contains recrystallized, 6 mm-diameter accretionary lapilli at the base that fine upward, indicating bedding-top direction to the north (Fig. 23c).

Cleaverville Formation (*AGlci*)

Strongly sheared chert and banded iron-formation form prominent ridges within, and parallel to, the Tabba Tabba Shear Zone in the northwestern corner of Carlindie. The rocks are interpreted as either primary chemical sediments or silicified shale and have been assigned to the Cleaverville Formation of the Gorge Creek Group. This is based on near-complete continuity, in both outcrop and geophysical trace, with similarly assigned rock to the southwest, on Satirist and Wallaringa (Smithies and Farrell, 2000; Smithies et al., 2002).

Banded iron-formation (*AGlci*), with local chert, forms narrow ridges up to 100 m wide and up to 5 km long in the Tabba Tabba Shear Zone, where they are tectonically interleaved with amphibolite-facies metagabbro (*Aog*) and schistose talc–carbonate rocks (*Auts*) and metaperidotites (*Aup*). Banded iron-formation (*AGlci*) shows layering on a 1 to 15 mm scale, which is typically tectonically disrupted, but in places is continuous at outcrop scale. Bands of recrystallized chert are fine- to medium-grained granoblastic quartz, and are typically strongly limonitized. Dark layers comprise opaque minerals (generally hematite), quartz, grunerite, garnet, graphite, and apatite, with some samples containing separate opaque-rich and grunerite (garnet)-rich layers. Strongly sheared layers of grunerite schist, with up to 85% grunerite, are locally up to 10 cm thick. At some localities they show well-developed layering defined by grain-size variations and variable



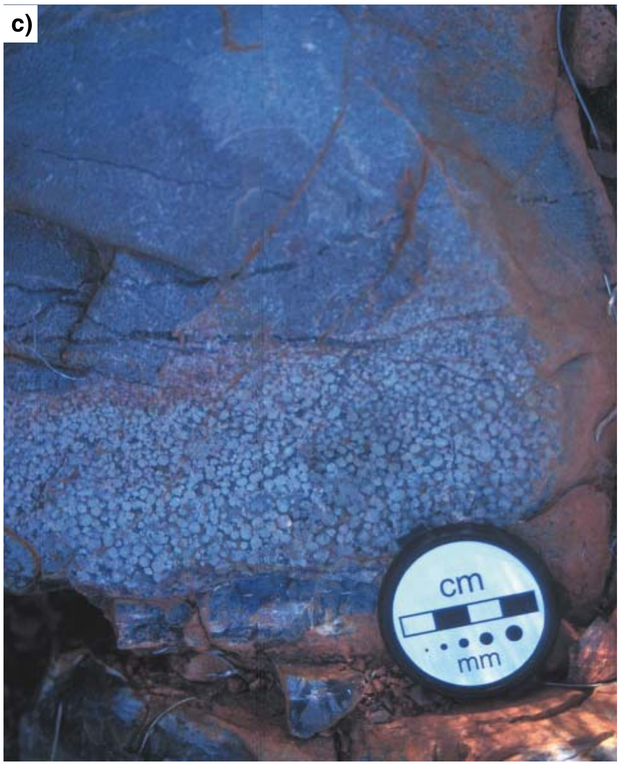


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Figure 23. The Paddy Market Formation, Gorge Creek Group: a) weakly folded red and black layered banded iron-formation (*AGpci*; MGA 756120E 7689400N); b) grey and white layered chert, after shale (*AGpshz*; MGA 751870E 7678350N); c) bed containing ooids in silicified fine-grained sedimentary rock (*AGpshz*; MGA 751870E 7678350N)

abundances of graphite, garnet, and goethite. Graphite-rich layers, up to 4 mm thick, preserve fine-scale laminations, but have been totally replaced by garnet, which has in turn been partly recrystallized to grunerite. Grunerite is locally recrystallized to actinolite and quartz. The garnet-rich layers probably represent original graphitic and ferruginous pelitic sediments. Local 'tiger's eye' asbestos forms thin layers in some outcrops.

Unassigned rocks of the Pilbara Supergroup (*Aog*, *Aup*, *Auts*, *Accq*, *Aba*, *Aut*, *Aux*, *Abas*, *Abks*, *Acc*, *Accw*, *Afs*, *Aft*)

Strongly deformed greenstones in the Tabba Tabba Shear Zone and in the northern part of the Warralong greenstone belt, north of the Marble Bar Road, and greenstone xenoliths in the Carlindi Granitoid Complex cannot confidently be ascribed to the Coonterunah or Warrawoona Groups (from which they were probably derived), and are thus designated as unassigned rocks of the Pilbara Supergroup. Lithologies are described below according to their distribution on Carlindie.

Tabba Tabba Shear Zone

Igneous protoliths of medium- to coarse-grained metagabbro (*Aog*) were emplaced into rocks of the Mallina Basin along the northwest margin of the Tabba Tabba Shear Zone at between c. 2970 and 2950 Ma (Smithies et al., 2001, 2002). Smithies and Champion (2002) suggested that the gabbroic protoliths represent the earliest magmatism related to voluminous c. 2950 Ma granodiorite magmatism within the Pippingarra Granitoid Complex. Petrographically, the metagabbro (*Aog*) on CARLINDIE is typically medium to coarse grained, and moderately to well foliated. Metamorphic actinolite is the sole mafic phase, forming ragged crystals and aggregates, but also clearly pseudomorphs subhedral to euhedral primary hornblende, and possibly also pyroxene. Plagioclase is an intergranular phase and is now partly to completely altered to a combination of sericite, an epidote mineral, and calcite. Coarse-grained, serpentinized peridotite (*Aup*) outcrops in the northern part of the shear zone.

Sheared talc–serpentine–chlorite–carbonate schists (*Auts*) in the Tabba Tabba Shear Zone contain interleaved slivers of the Cleaverville Formation (banded iron-formation and chert), quartz–sericite schist and cordierite hornfels derived from probable Mallina Formation metasediments, and actinolite schist. The unit of unassigned layered white and grey chert and white quartzite (*Accq*) in the southwest of the shear zone contains minor ferruginous chert layers and probably represents Gorge Creek Group protoliths that have been silicified and sheared.

Carlindi Granitoid Complex

Medium-grained amphibolite (*Aba*) outcrops in one locality in the Carlindi Granitoid Complex (MGA 713400E 7695900N), interlayered with massive- to well-foliated, medium-grained serpentinized peridotite (*Aup*). The amphibolite is moderately foliated and lineated and consists of equigranular to slightly aligned grains of hornblende, plagioclase, and titanite with traces of zircon and apatite. A large inclusion of talc–serpentine–chlorite schist (*Aut*) outcrops in the southwest corner of CARLINDIE (MGA 712000E 7678000N). These rocks probably correspond to xenoliths of the Coonterunah and Warrawoona Groups.

Massive peridotite (*Aup*) outcrops in three small exposures in the north-central part of CARLINDIE (MGA 736200E 7715000N), and correlate well with a curvilinear high-magnetic zone. A kilometre-long, low ridge of massive, coarse-grained pyroxenite (*Aux*; MGA 731000E 7690000N) is composed of centimetre-sized orthopyroxene phenocrysts in a medium-grained matrix of chlorite and tremolite(–?actinolite). These rocks are interpreted to represent ultramafic intrusions, most likely related to the Dalton Suite identified on NORTH SHAW (Van Kranendonk, 1998, 2000).

Northern part of the Warralong greenstone belt

Rocks in the northern part of the Warralong greenstone belt are strongly deformed and metamorphosed to lower amphibolite to upper greenschist facies. Panels of strongly deformed, amphibolite schists (*Abas*; MGA 760100E 7705000N) may contain layers of ultramafic schist and chert, indicating derivation from a succession of supracrustal rocks, most likely of the Warrawoona Group. The amphibolites are strongly foliated and lineated, with equigranular but well-aligned grains of hornblende–plagioclase and titanite. Tremolite–chlorite–serpentine and talc–carbonate–chlorite schists (*Abks*) in the same area are interpreted as metamorphosed and deformed komatiitic basalts, and enclose subordinate chlorite–epidote–plagioclase–quartz(–carbonate) schists (metabasalt) and massive to weakly layered grey chert (*Acc*) and well-layered grey, white, and blue-black chert (*Accw*).

Serpentinized peridotite (*Aup*) in the northern part of the Warralong greenstone belt (MGA 760200E 7705000N) is variably deformed with schistose serpentine–chlorite margins, but have cores of relatively well preserved rock with serpentinized olivine crystals rimmed by unidentified opaque minerals and enclosed in a fine-grained groundmass.

A tight, south-plunging syncline of highly strained quartz–sericite schists (*Afs*) and silicified, fine- to coarse-grained felsic tuffaceous rock (*Aft*), about 3 km east of No. 8 Well (MGA 759400E 7702800N), includes quartz-rich volcaniclastic sandstone and layers of pale creamy yellow-weathering chert (?porcellanite). Fine-grained quartz–sericite schist (*Afs*) locally contains centimetre-sized porphyroblasts of kyanite and abundant muscovite (Fig. 24; MGA 760200E 7703350N). These rocks probably represent a northerly continuation of either the Duffer or Panorama Formations of the Warrawoona Group.

Strongly recrystallized and tightly folded cherts form several small outcrops of mafic and ultramafic schist in the northern part of the Warralong greenstone belt. Several thin units of undivided chert (*Acc*), including grey to blue-black chert with either no, or poorly defined, layering, outcrop over small areas in the northern part of the Warralong greenstone belt. Other cherts have a better layering defined by centimetre-thick, alternating blue-black, grey, and white chert layers (*Accw*).

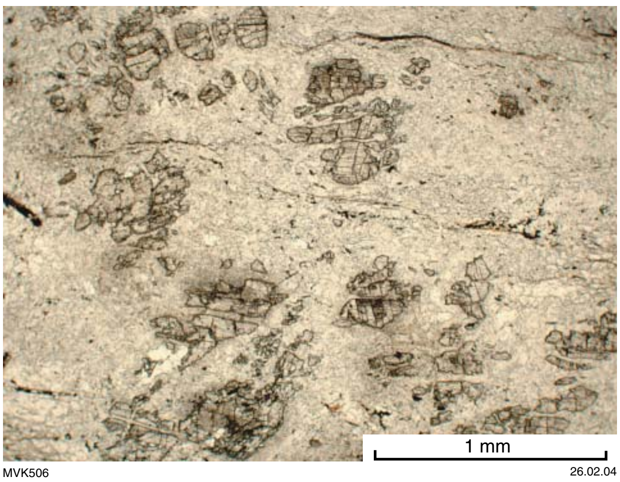

Figure 24. Kyanite-bearing, porphyroblastic felsic schist (*Afs*) from the northern part of the Warralong greenstone belt (plane-polarized light; MGA 760150E 7703300N)

De Grey Group

The Lalla Rookh Sandstone of the De Grey Group outcrops in the Lalla Rookh Synclinorium in southeastern CARLINDIE. De Grey Group rocks (Mallina Formation) are also interpreted to underlie part of the Tabba Tabba Shear Zone in the northwestern corner of CARLINDIE (Figs 3 and 4), based on interpretation of magnetic data and geology of the adjacent WALLARINGA sheet map (Smithies et al., 2002). The Lalla Rookh Sandstone reaches an approximate thickness of 4500 m, although this is a minimum depositional thickness because the basal or top contacts (or both) are faulted.

Interbedded shale, siltstone, and medium- to fine-grained wacke of the Mallina Formation (*ADm*) is interpreted to underlie part of the northwestern corner of CARLINDIE, but is concealed on CARLINDIE. Smithies et al. (2002) described small outcrops of laminated and ferruginous, locally chloritic shale, and poorly sorted wacke with grey chert fragments and clasts of shale and basalt near the boundary with WALLARINGA. Close to granitic contacts, rocks of the Mallina Formation are contact metamorphosed to cordierite hornfels (see Smithies et al., 2002). The latest movement along the Tabba Tabba Shear Zone has affected the contact metamorphic assemblage, and so the intrusive age of the granitic rocks (c. 2940 Ma) represents a maximum age of shearing. Geochronological data from southwest of CARLINDIE indicate deposition of the Mallina Formation at c. 2970–2955 Ma (Smithies et al., 2001).

Lalla Rookh Sandstone (*ADlst*, *ADlstq*, *ADlsh*, *ADlsc*, *ADlscx*)

The dominant component of the Lalla Rookh Sandstone is a pale-orange-weathering, coarse-grained to pebbly sandstone (*ADlst*) that exhibits well-developed bedding averaging 30 cm in thickness, graded bedding, and cross-bedding. The lower parts (to ~1000 m stratigraphic height) of the sandstone include common 1–10 m-thick beds of pebble to cobble conglomerate, whereas sandstones higher up are more homogeneous and medium grained, with local beds of quartz-rich sandstone (*ADlstq*). Locally, metre-thick conglomerate beds in coarse sandstone are almost monomictic, with clasts up to 20 cm across, about 90% of which are composed of milky white quartz, and about 10% are subordinate grey-white layered chert (MGA 756500E 7689500N). Conglomerate beds are at higher stratigraphic levels, in the core of the syncline (MGA 754000E 7681000N). Green-weathering shale and siltstone (*ADlsh*) at the highest stratigraphic level of the formation in the core of the Lalla Rookh Synclinorium is commonly not exposed, except for one outcrop in the bend of an unnamed creek (MGA 753500E 7683000N).

A basal conglomerate is developed where the formation unconformably overlies the Gorge Creek Group on the northern limb of the Lalla Rookh Synclinorium. In the far northeast (MGA 758200E 7690100N), this basal pebble to cobble conglomerate (*ADlsc*) contains well-rounded clasts of layered grey and white chert, white quartz, quartz-rich sandstone, and (less common) silicified volcanic rocks in a matrix of coarse sand. At the eastern boundary of CARLINDIE (MGA 760000E 7690800N), basal conglomerate of the Lalla Rookh Sandstone lies on quartz-rich sandstone of the Gorge Creek Group (*AGcstq*) and is composed of well-rounded quartz-rich sandstone clasts in a white to beige quartz-rich sandstone matrix, indicating proximal development of the conglomerate. Farther southwest (MGA 754000E 7688700N), a small lens (<75 m thick and 320 m long) of the basal conglomerate (*ADlscx*) contains angular fragments, less than 12 cm across but averaging 2–5 cm, of underlying black and blue-grey layered chert and sandstone that lie in a siliceous matrix with quartz or chert sand (or both). Typical pale-orange-weathering coarse sandstone of the Lalla Rookh Sandstone laps onto this lens of breccia and underlying rocks of the Gorge Creek Group at this locality.

Late-tectonic and unassigned granites of the Carlindi Granitoid Complex (*AgLm*, *AgLmm*, *AgLmp*, *AgLmi*, *AgL*)

Blue-grey, fine- to medium-grained biotite monzogranite (*AgLm*) outcrops in the southwestern corner of CARLINDIE (MGA 708500E 7676750N) and near the contact with the Warralong greenstone belt in the southeast (MGA 754100E 7695750N). This unit is also inferred from magnetic data to underlie a third locality in the southwest, where it is not exposed (see Interpreted bedrock geology figure on main map). This unit forms distinctive outcrops, characterized by rounded boulders with dark-brown-weathering rinds, distributed in pyramidal tors of delicately balanced boulders. The rocks are commonly silicified. No foliation was observed in this unit. In thin section the rock contains medium- to coarse-grained K-feldspar (to 0.5 cm) that is zoned and contains minor myrmekite clots. Clumps of coarse euhedral titanite, coarse epidote, and biotite are within a matrix of predominantly medium-grained quartz and plagioclase that show abundant evidence of deformation in the form of multiple subgrains of quartz and kinked feldspars. However, the rock displays no obvious foliation either in outcrop or thin section, such that the deformation features are interpreted as synmagmatic. This unit is identical in appearance and strain state to the c. 2930 Ma Mulgandinnah Monzogranite of the Shaw Granitoid Complex (Van Kranendonk, 2000), but a sample dated at 3484 ± 4 Ma (Nelson, 1999; GSWA 153188) may reflect an inherited xenocrystic age population of zircons.

Mylonitized monzogranite (*AgLmm*) within the Tabba Tabba Shear Zone displays strongly foliated to mylonitic textures that include penetrative foliations and lineations defined by quartz ribbons and smeared out, recrystallized feldspar aggregates, and by biotite–chlorite clots. The rocks are medium grained and homogeneous, without leucosome veins, suggesting that they are monocyclic and younger than the 3470 Ma TTG suite (Wilson Well Gneiss — *AgLwi*; Motherin Monzogranite — *AgLut*) and probably c. 3300, 3250, or 2940 Ma in age. This is supported by geochronology data from a sample of foliated granodiorite (GSWA 160745; Nelson, 2001) that returned an age of

2940 ± 3 Ma, which is interpreted as the igneous emplacement age (see Table 2). Interlayered with these more homogeneous intrusions are layered blue-grey tonalitic rocks of the Wilson Well Gneiss (*AgLwi*) with leucocratic pegmatite veins. K-feldspar-porphyritic, biotite monzogranite (*AgLmp*) also outcrops in this zone.

The Minnamonica Monzogranite (*AgLmi*) is a grey to white, medium-grained, muscovite(–biotite) monzogranite with equigranular to sparsely quartz–feldspar-porphyritic textures that outcrops in the southwestern part of CARLINDIE where it shows clearly crosscutting relationships with older, deformed tonalitic orthogneiss. The monzogranite varies from massive to very weakly foliated. Sparse feldspar phenocrysts (<3% of the rock) are up to 1.5 cm across and quartz phenocrysts are up to 1 cm across. Muscovite is the dominant mica mineral on CARLINDIE (5–6% of the rock with grains up to 5–8 mm in size), with subordinate biotite (<3% of the rock). Mica are locally concentrated into schlieren. The unit contains rare biotite-rich or granodioritic enclaves, up to 15 cm in size, as well as rare pegmatite dykes that extend into the host rocks. The unit is strongly oxidized, forming a magnetic low.

Unassigned granitic rock (*AgL*) intrudes the Coonterunah Group along the western margin of the Warralong greenstone belt. Most of these granitic rocks are strongly foliated, medium grained, and contain biotite. The age of these rocks is unconstrained, but they must be younger than the rocks they intrude (c. 3500 Ma), and older than the c. 2940 Ma shear deformation that has affected them.

Post-tectonic granites of the Carlindi Granitoid Complex

Undivided (*AgLpe*)

Swarms of pegmatite veins and small outcrops of pegmatitic monzogranite (*AgLpe*) are adjacent to the main outcrop areas of the post-tectonic Kimmys Bore Monzogranite (*AgLkb*; MGA 709500E 7683000N) and Kadgewarrina Monzogranite (*AgLkd*; MGA 718300E 7708000N), as well as near the Strelley Mine in northwestern CARLINDIE (MGA 709800E 7728000N), which has coarse muscovite and has been exploited for tantalum and beryl (see **Economic geology**). These pegmatite veins contain coarse to extremely coarse K-feldspar crystals that commonly have granophyric quartz-exsolution blebs, and patches of coarse interstitial quartz and muscovite with or without biotite and tantalite and beryl crystals in places. Some pegmatites form subhorizontal sheets (e.g. MGA 719250E 7709050N), whereas the swarm of veins in the southwestern part of CARLINDIE form subvertical dykes.

Kadgewarrina Monzogranite (*AgLkd*, *AgLkdb*, *AgLkdn*, *AgLkdpe*)

The undeformed Kadgewarrina Monzogranite outcrops in two main areas in the central-western part of CARLINDIE (see Interpreted bedrock geology figure on main map). It has a subhorizontal basal contact with older gneisses (e.g. *AgLwi*), observed in outcrop, and contains widespread igneous layering that dips at shallow to moderate angles (see Diagrammatic section A–B on main map). There are two main phases of this layered granite. The most widespread phase in outcrop is a layered, equigranular to K-feldspar-porphyritic, medium-grained to pegmatitic, muscovite–biotite(–garnet) monzogranite (*AgLkd*). Igneous layering in this unit consists of sheets of pegmatitic monzogranite, several metres thick, that pass into medium- to coarse-grained, equigranular to porphyritic monzogranite across gradational, though relatively sharp, boundaries (Fig. 25). This layering is flow folded. The other main unit of the Kadgewarrina Monzogranite is a homogeneous, fine-to medium-grained, equigranular biotite monzogranite (*AgLkdb*). Near the margins of the monzogranite, particularly along the basal contact, the monzogranite (*AgLkdn*) is markedly more heterogeneous, containing enclaves of the surrounding orthogneiss (*AgLwi*), displaying a schlieric texture, and cut by numerous garnet–muscovite pegmatite dykes. Garnet–tourmaline pegmatitic monzogranite veins (*AgLkdpe*) cut orthogneisses near the margins of the main plutonic bodies, and locally contain large beryl crystals (to 10 cm, near Turkey Camp Well; MGA 717650E 7699100N).

The Kadgewarrina Monzogranite has not been directly dated. However, a sample of a crosscutting dolerite dyke of the Mundine Well dyke swarm contains several slightly

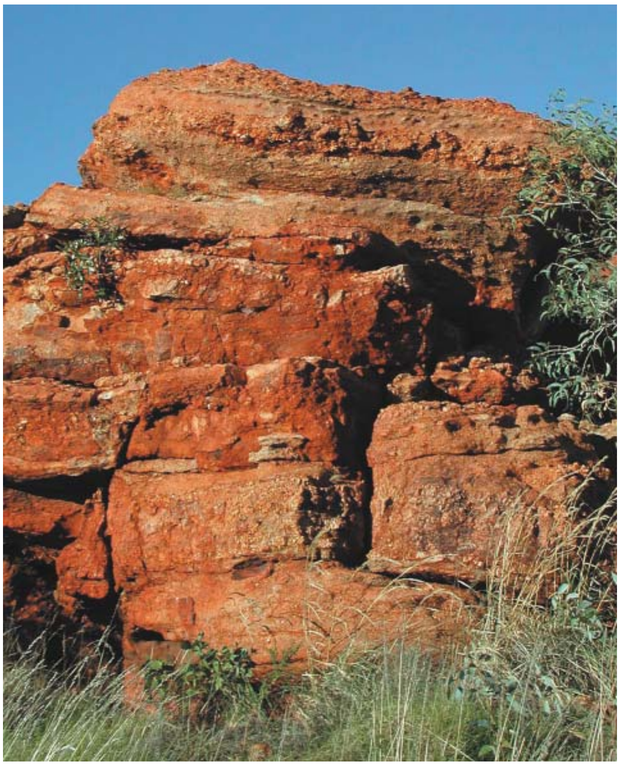

Figure 25. The Kadgewarrina Monzogranite (*AgLkd*), showing shallow-dipping igneous layering between pegmatitic (central and top parts of outcrop) and more equigranular (bottom and upper parts of outcrop) sheets (712500E 7696800N)

to highly discordant inherited zircons with $^{207}Pb/^{206}Pb$ ages between 2870 and 2845 Ma (Table 2; Wingate and Giddings, 2000), which give a pooled mean age of 2859 ± 2 Ma (Wingate, M. T. D., University of Western Australia, written comm., 2003) and are interpreted to represent the age of the Kadgewarrina Monzogranite.

Kimmys Bore Monzogranite (*AgLkb)*

The Kimmys Bore Monzogranite (*AgLkb*) outcrops in the southwestern part of CARLINDIE, where it is moderately well exposed. It is a medium- to coarse grained, biotite(–muscovite) monzogranite with scattered K-feldspar phenocrysts to 1 cm. Thin section petrography reveals this as a commonly coarse grained, undeformed granite with pristine igneous textures, including coarse-grained feldspar with long contacts, perthitic exsolution in K-feldspars, and myrmekite blebs where muscovite crystallized in late fluid-rich interstitial patches (Fig. 26).

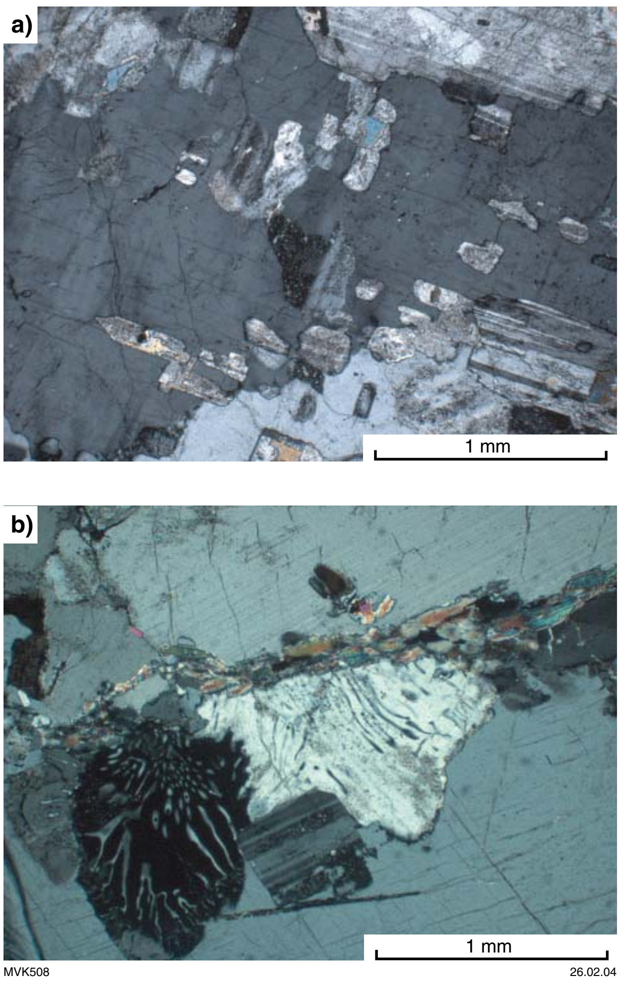

Figure 26. The Kimmys Bore Monzogranite: a) perthite exsolution of plagioclase (light blebs) in K-feldspar (*AgLkb*); b) myrmekite at a plagioclase–K-feldspar grain boundary (cross-polarized light; (719800E 7681600N)

Structural geology of the northern part of the Pilbara Craton

CARLINDIE is dominated by a northeast-trending structural grain that is concentrated in areas of greenstone outcrop in the Warralong greenstone belt in the southeast, and in the Tabba Tabba Shear Zone in the northwest. A total of seven sets of structures that are restricted to the basement granite–greenstone terrane of the northern part of the Pilbara Craton (i.e. pre-Fortescue Group) are recognized on CARLINDIE, and are divided into four main deformation events following the scheme proposed by Van Kranendonk et al. (2002). The history of deformational events in the Warralong greenstone belt is well constrained by several unconformities in the stratigraphy and by geochronological data on samples from key stratigraphic horizons. A summary of the structural development of CARLINDIE is provided in Table 3.

D_1 deformation

Evidence for a D_1 deformation event on CARLINDIE, between c. 3470 and 3430 Ma (Van Kranendonk et al., 2002), is indicated by a disconformable contact between the Panorama and Duffer Formations in the Warralong greenstone belt and the nondeposition, or erosion, of the intervening Apex Basalt that outcrops elsewhere. Further evidence of an early period of deformation is provided by the erosional unconformity at the base of the Strelley Pool Chert (<3426 Ma, >3350 Ma), which is marked by the development of thick quartz-rich sandstones that lie on different formations in different parts of the Warralong greenstone belt (on the Coonterunah Group in the west and on the Panorama Formation of the Warrawoona Group in the east).

D_1 structures in the Carlindi Granitoid Complex include a set of folded migmatitic leucosome veins in c. 3470 Ma TTG gneisses (e.g. Wilson Well Gneiss, *AgLwi*). These are locally cut by relatively homogeneous (nonmigmatitic), but foliated tonalitic rocks that are interpreted to be part of a c. 3430 Ma suite (see Fig. 5c) based on field and geochronological data from the Shaw Granitoid Complex on TAMBOURAH (Van Kranendonk, 2003a).

D_2 deformation

Following deposition of the Euro Basalt at c. 3350–3325 Ma, a local period of tilting (D_{2a}) is inferred from the disconformable contact of the Wyman Formation on the Euro Basalt (e.g. Fig. 10). Deposition of the lowest unit of the Wyman Formation, at c. 3324 Ma on CARLINDIE (see **Geochronology**), was accompanied by hydrothermal circulation and synsedimentary faulting (D_{2b}; see Fig. 10), all of which are inferred to be local effects of (possible) volcanic instability and are thus indicated as subsets of the regional D_2 deformation between c. 3325 and 3310 Ma.

Table 3. Summary of deformational events and their age on CARLINDIE compared to regional events

Estimated age (Ma)	*Tabba Tabba Shear Zone*	*Carlindi Granitoid Complex*	*Warralong greenstone belt / Lalla Rookh – Western Shaw Structural Corridor (scheme adapted herein)*	*Regional deformation events (Van Kranendonk et al., 2002)*
<755	–	North–south faults	North–south faults	–
?	–	–	D_{F5} tilting of Kylena Formation	–
<2756	–	–	D_{F4} gentle tilting of Hardey Formation	–
<2772 >2756	–	–	$\mathbf{D_{F3}}$ folding and faulting of Mount Roe Basalt	$\mathbf{D_6}$
c. 2775	–	–	D_{F2} east–west extension during deposition of Mount Roe Basalt	–
<2830 >2775	–	–	D_{F1} compressional folding of Bellary Formation of the Fortescue Group	–
c. 2890	–	–	–	D_5
c. 2940–2930	Greenschist-facies sinistral shearing	D_4 shear transposition	$\mathbf{D_{4b}}$ sinistral transpression; folding and faulting of greenstones	$\mathbf{D_4}$ sinistral transpression
c. 2970–2955	Deposition of Mallina Formation; intrusion of mafic rocks and granites (Pippingarra Granitoid Complex); amphibolite-facies metamorphism and shear deformation	–	D_{4a} tilting of Warralong greenstone belt; metamorphism and shearing in Tabba Tabba Shear Zone	–
c. 3235	–	–	D_{3b} growth faults during Gorge Creek Group deposition	–
c. 3255–3235	–	D_3 foliation and folding	D_{3a} tilting of greenstones during deposition of the Sulphur Springs Group	$\mathbf{D_3}$ renewed doming
c. 3315–3310	–	–	$\mathbf{D_{2c}}$ tight folding of greenstones	$\mathbf{D_2}$ Major doming event
c. 3325–3315	–	–	D_{2b} extensional growth faulting during deposition of the Wyman Formation	–
~3325	–	–	D_{2a} local tilting of Euro Basalt prior to deposition of Wyman Formation	–
?c. 3450–3350	–	–	D_{1b}: tilting of greenstones represented by unconformity at base of Strelley Pool Chert on older rocks	–
c. 3470–3450	–	D_{1a} leucosome vein generation and folding	$\mathbf{D_{1a}}$ disconformity of Panorama Formation on Duffer Formation	D_1 synvolcanic doming

NOTE: Deformation events in bold represent major events

Following deposition of the remainder of the Wyman Formation, the rocks were folded into an open syncline during regional D_{2c} deformation at c. 3310 Ma, as deduced from data elsewhere in the EPGGT (Collins et al., 1998; Bagas et al., 2003; Van Kranendonk et al., 2002), although the exact age of this deformation is not directly constrained on Carlindie. This event was responsible for a large component of the amplitude of the Warralong Syncline, as evidenced by the fact that the Sulphur Springs Group and the conformably overlying Gorge Creek Group are deposited on parts of the Warrawoona Group that have been folded into markedly different structural orientations (see cross section C–G on map). Unfolding the effects of younger D_3 and D_4 deformation events shows that the bulk of folding of the Warrawoona Group occurred before deposition of the Sulphur Springs Group at c. 3255–3235 Ma (Fig. 27; age data from Buick et al., 2002).

D_3 deformation

Deposition of the Sulphur Springs Group was accompanied by tectonic instability (D_{3a}), as demonstrated by the disconformable contact between the Kunagunarrina and Kangaroo Caves Formations of the group (Figs 13, 15, and 19). This relatively minor deformational episode on Carlindie correlates with regional D_3 deformation across the EPGGT (Table 3; Van Kranendonk et al., 2002), which is interpreted as a period of widespread granite intrusion and localized strong, high-grade deformation associated with renewed doming of the major granitic complexes (Van Kranendonk, 1997, 2000).

Deposition of the Gorge Creek Group, which succeeded the Sulphur Springs Group from c. 3235 to 3020 Ma, was accompanied by the local development of north-northeasterly striking growth faults (D_{3b}). This is indicated by significant depositional thickness variations (100 to 1300 m) in the Corboy Formation where it strikes easterly and lies unconformably on the Warrawoona Group at the far-eastern edge of Carlindie (MGA 759400E 7692000N; see Fig. 27; Van Kranendonk et al., in press). Growth faulting resulted in rotation of the Corboy Formation by up to 45° at the eastern boundary of Carlindie. These structures are also on the adjacent Coongan sheet (Van Kranendonk, 2004).

Migmatitic gneisses are cut by homogeneous, strongly foliated but nonmigmatitic monzogranites (*AgLmh*), dated at c. 3252 Ma (Fig. 5d; see **Geochronology** below). These intermediate-age granitic rocks contain a well-developed, east-striking foliation that is tightly folded about south-southwesterly plunging axes that are correlated with regional sinistral transpression (D_{4b}). The age of the folded foliation in these granitic rocks is unknown, but must be less than 3252 Ma (the intrusive age of the rock), and more than 2940 Ma (the age of D_{4b} deformation), and thus probably formed during D_{3a} deformation (see Table 3).

D_4 deformation

Deposition of the Gorge Creek Group was followed by gentle (commonly <10°) tilting of the greenstones into interpreted interdiapir synclines (D_{4a}; Van Kranendonk et al., in press) and then by deposition of the De Grey Group, which was synkinematic with regional sinistral transpression (D_{4b}) at c. 2940–2930 Ma (Van Kranendonk and Collins, 1998). Deposition of the De Grey Group in the Mallina Basin (Constantine Sandstone and Mallina Formation) occurred from 2970 to 2940 Ma, and was accompanied by several phases of diverse magmatism and at least two pulses of deformation (Smithies et al., 2001). Deposition of the Lalla Rookh Sandstone in the EPGGT probably occurred at, or before, c. 2940–2930 Ma. This is the age of granite magmatism that was syntectonic with the regional transpression with which deposition of the Lalla Rookh Sandstone is associated (Krapez and Barley, 1987; Van Kranendonk and Collins, 1998; Zegers et al., 1998).

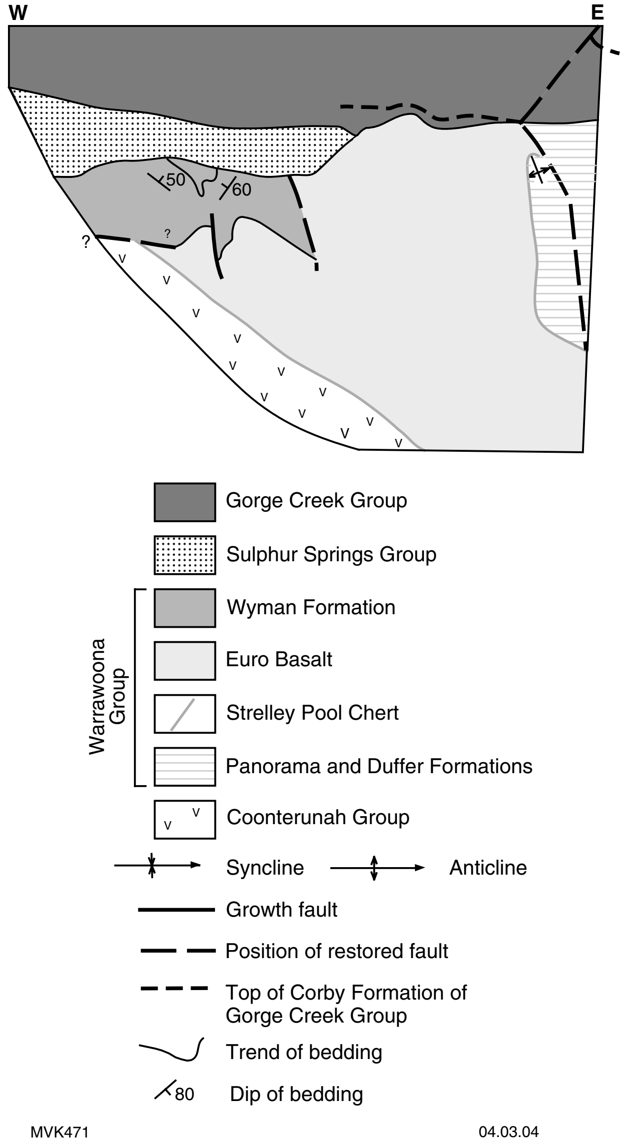

Figure 27. Schematic restored west–east cross section of the Warralong greenstone belt, before regional D_3 deformation, showing the large-scale, tight, D_{2c} fold of the Warrawoona Group that formed before deposition of the Sulphur Springs and Gorge Creek Groups

D_{4b} structures on CARLINDIE include:

- all the tight folds and faults that affect the Lalla Rookh Sandstone in the Lalla Rookh Synclinorium;
- the complex and branching, northeast-striking sinistral fault set along the western margin of the Lalla Rookh Synclinorium that extends north through the axis of the Warralong Syncline;
- the sinistral Lalla Rookh – Western Shaw fault along the western margin of the Warralong greenstone belt whose position is inferred from magnetic maps;
- the faults that cut the Panorama greenstone belt.

D_{4b} folds of the Lalla Rookh Sandstone are northeasterly to east-northeasterly plunging, upright structures, whereas a large-scale D_{4b} syncline developed in the Sulphur Springs and Gorge Creek Groups plunges to the southwest. North- to northeast-striking faults are sinistral, but easterly striking faults are probably dextral on the basis of an east-directed offset between a panel of stratigraphically lower quartzite of the Corboy Formation (*AGcstq*) and stratigraphically overlying banded iron-formation of the Paddy Market Formation (*AGpci*; MGA 755000E 7689380N). No kinematic indicators were directly observed on these faults. North-northwesterly striking sinistral faults along the eastern edge of CARLINDIE (MGA 758500E 7692500N and 759800E 7693250N) cut all lithology including the Lalla Rookh Sandstone (Fig. 28) and offset the northeast-striking D_{3b} growth faults. Thus, the D_{4b} sinistral and dextral faults on CARLINDIE constitute a conjugate set of structures to accommodate approximately northwest–southeast compression, as found throughout the Lalla Rookh – Western Shaw Structural Corridor, of which this forms the northern part (Van Kranendonk and Collins, 1998).

Penetrative D_{4b} foliations are interpreted to extend for about 12 km west of the Warralong greenstone belt margin (Lalla Rookh – Western Shaw fault) into the Carlindi Granitoid Complex, based on patterns on magnetic maps. Penetrative metamorphic foliations associated with this deformation also extend for about 700 m east of the fault into the stratigraphically and structurally lowest, amphibolite-facies part of the Warralong greenstone belt (e.g. Coonterunah Group at MGA 754500E 7694500N).

Structures ascribed to regional D_{4b} sinistral transpression include a strong transposition foliation along the eastern margin of the Carlindi Granitoid Complex, and possibly the large-scale folds in the northwestern part of the complex, both of which are clearly recognizable on regional aeromagnetic images (see Interpreted bedrock geology figure on map). All of these structures are cut by the post-tectonic, c. 2860 Ma Kagdewarrina and Kimmys Bore Monzogranites (see Table 1 and the Interpreted bedrock geology figure and Diagrammatic section A–B on map).

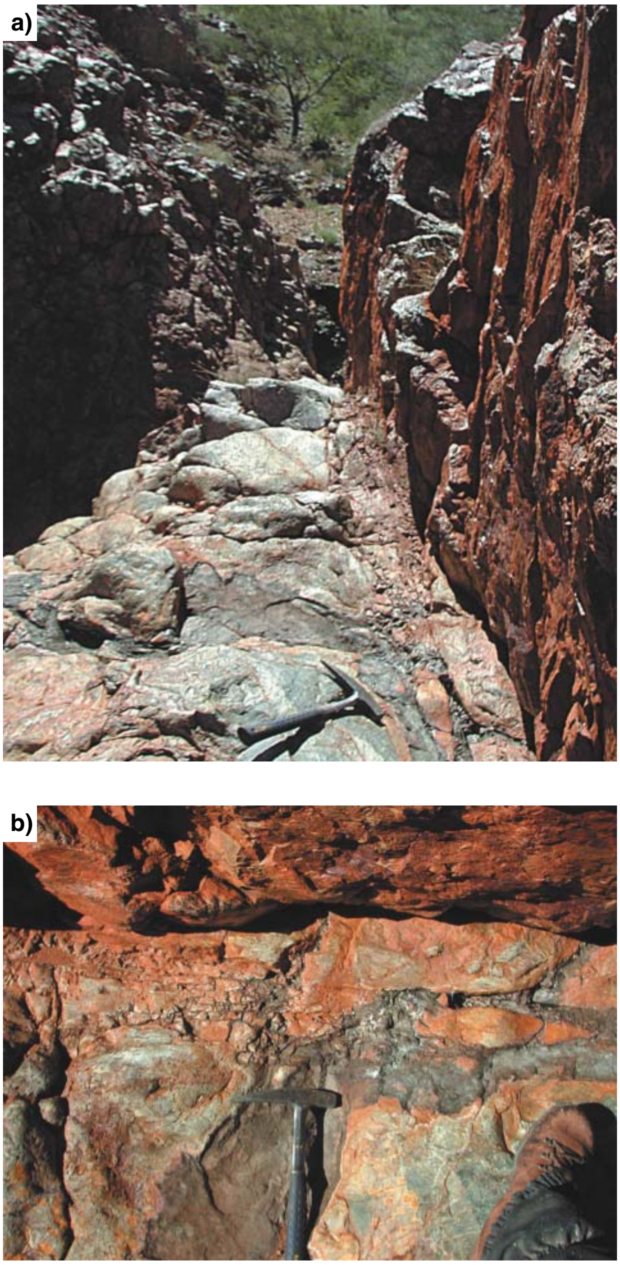

Figure 28. Outcrops of a north-northwesterly striking D_{4b} fault (MGA 759900E 7692850N): a) view north-northwest of fault, just right of hammer, between quartz-rich sandstone of the Strelley Pool Chert (*AWsstq*) on the right and Lalla Rookh Sandstone (*ADlst*) on the left; b) view looking down, facing east, of the horizontal outcrop surface in (a), showing multiple fractures splaying off from the main fault

Tabba Tabba Shear Zone

The northeast-trending Tabba Tabba Shear Zone (D_4) cuts through the northwestern part of CARLINDIE (Figs 3 and 4) and forms the southeastern margin of the Mallina Basin (Smithies et al., 2002). Three deformational phases are identifiable in the shear zone: a major oblique sinistral phase, an early dextral phase, and a minor late dextral phase (Smithies et al., 2001; Smithies et al., 2002; Beintema, 2003).

On CARLINDIE sinistral D_{4b} kinematic indicators were recognized in deformed mafic rocks in the core of the shear zone, defined by S–C–C’ textures in retrograded greenschist-facies mafic schists. These steeply easterly dipping foliations contain a moderately easterly plunging mineral elongation lineation defined by chlorite, both of which overprint amphibolite-facies D_{4a} structures, including moderately northeasterly plunging mineral elongation lineations defined by hornblende. About 1 km farther east, deformed granitic rocks of the Carlindi Granitoid Complex contain sinistral kinematic indicators and elongate quartz grains plunging moderately to the south.

Smithies and Champion (2002) showed that the main period of sinistral shear in the Tabba Tabba Shear Zone was associated with local extension in west-southwesterly striking segments of the zone (i.e. the Wallareenya jog). They interpreted the sinistral extensional phase of deformation in the Tabba Tabba Shear Zone to be from before 2955 to c. 2945 Ma (D_{4a}). Dating of strongly foliated late monzogranite (*AgLmm*; Nelson, 2001) along the southeastern edge of the shear zone on CARLINDIE extends the period of activity to at least 2940 ± 3 Ma (D_{4b}), which coincides with the latest depositional event within the Mallina Basin (Smithies et al., 2001).

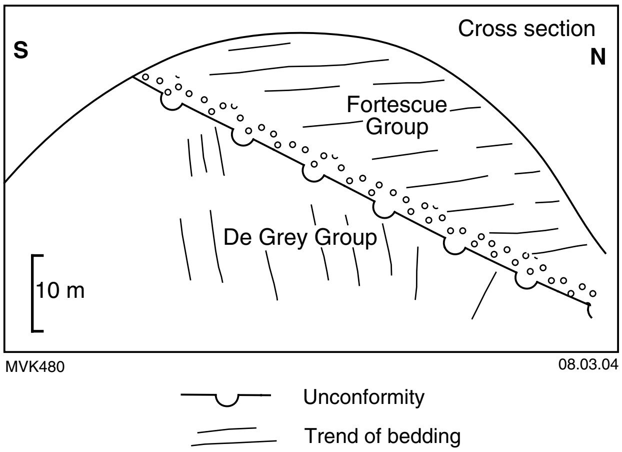

Figure 29. Diagrammatic sketch of the basal unconformity of the Fortescue Group (MGA 759050E 7688100N), looking west at a hillside with vertically dipping strata of the Lalla Rookh Sandstone (De Grey Group) beneath an onlapping sequence of coarse clastic rocks belonging to the Bellary Formation of the Fortescue Group

Lithostratigraphy of the Fortescue Group

Rocks belonging to the Fortescue Group of the Mount Bruce Supergroup outcrop in the southeastern corner of CARLINDIE, as an east- to southeast-dipping panel on the northwestern side of the Marble Bar Sub-basin of the Hamersley Basin. On CARLINDIE the Fortescue Group consists of basal siliciclastic rocks herein ascribed to the Bellary Formation, the unconformably overlying Mount Roe Basalt, clastic rocks of the Hardey Formation, and basalt flows of the Kylena Formation. The Fortescue Group reaches a maximum thickness of about 1850 m on CARLINDIE, but this is an incomplete stratigraphic section as the group continues up stratigraphy onto COONGAN and MARBLE BAR to the southeast (e.g. Van Kranendonk, 2003b). Rocks of the basal clastic succession and Mount Roe Basalt lie unconformably on the Lalla Rookh Sandstone of the De Grey Group, the Paddy Market Formation of the Gorge Creek Group, and the Euro Basalt of the Warrawoona Group on CARLINDIE.

Bellary Formation (*AFbsc*, *AFbst*)

The base of the Fortescue Group is marked by up to 100 m of thickly bedded, basal pebble conglomerate and sandstone (*AFbsc*) and up to 1000 m of overlying coarse to pebbly sandstone and minor conglomerate (*AFbst*), both of which are unconformably overlain by the Mount Roe Basalt. The sedimentary rocks are matrix supported and contain well-rounded to subangular pebbles (<25 cm diameter) of blue-black chert and white quartz in a matrix of coarse, well-rounded quartz-rich sand. At one locality, flat-lying basal conglomerates and sandstones (*AFbsc*) onlap a palaeohigh, from north to south, of subvertically dipping sandstones of the Lalla Rookh Sandstone (*ADlst*; Fig. 29; MGA 759050E 7688100N). Overlying lithologies consist of coarse-grained, quartz-rich sandstones that commonly contain 20% sand grains of blue-black chert. These rocks are well bedded, with gravel lags, cross-bedding, and scours indicative of fluvial deposition. In the southern part of the outcrop area of the Fortescue Group (MGA 757000E 7677500N), the basal clastic succession cuts an incised channel, up to 300 m wide and tens of metres deep, into the Gorge Creek Group.

Mount Roe Basalt (*AFrb*)

The Mount Roe Basalt (*AFrb*) on CARLINDIE is up to 1120 m thick and commonly unconformably overlies the Bellary Formation, but locally lies directly on older basement rocks including the Gorge Creek Group and Euro Basalt of the Warrawoona Group. Bedding trends in the Mount Roe Basalt are oblique to those in the Bellary Formation, indicating an intervening period of tilting and erosion before deposition of the Mount Roe Basalt (e.g. MGA 756550E 7678800N and 759200E 7684200N; see **Structural geology of the Fortescue Group** below). The Mount Roe Basalt forms 50–300 cm-thick flows that are commonly highly vesicular, some with quartz-filled gas cavities and amygdales, although some flows are massive. Plagioclase-phyric and glomeroporphyritic flows are within the middle of the formation on CARLINDIE. Remnants of poorly developed pillows are at the top of the formation near the eastern edge of CARLINDIE, and at the base of the formation on the adjacent COONGAN sheet (Van Kranendonk, 2004). The volcanic rocks are commonly altered to chlorite–epidote assemblages with coarse pyroxenes and titano-ilmenites, and less common plagioclase and quartz phenocrysts.

Hardey Formation (*AFhst*)

The Hardey Formation on CARLINDIE consists dominantly of thickly bedded sandstone and pebbly sandstone (*AFhst*), but includes minor brown shale and pebble to cobble conglomerate that reach a combined maximum thickness of about 170 m. These rocks lie with erosional unconformity on the Mount Roe Basalt (see also Van Kranendonk, 2000). At the base of the formation is a thin unit of dark-green shale that drapes over the underlying lavas and passes up to siltstone and sandstone; these units form a combined thickness of 20–25 m. This lower member is overlain by cross-bedded medium- to coarse-grained sandstone with metre-thick, matrix-supported conglomerate beds containing subrounded white quartz clasts, up to 5 cm in diameter, in a coarse sand matrix. In the middle of the formation is a thin unit of pale-brown-weathering shale, which is overlain by thick-bedded sandstone capped by a cross-bedded granule to pebbly sandstone.

Kylena Formation (*AFkbx*, *AFkb*)

The Kylena Formation lies unconformably on the Hardey Formation. At the base of the Kylena Formation is a basaltic agglomerate (*AFkbx*), up to 168 m thick, with fragments of dominantly basalt and subordinate (?tuffaceous) shale, up to 6 cm across, in a matrix of welded basaltic glass shards (hyaloclastite). The top of this lower member is centimetre- to decimetre-bedded basaltic tuffs and agglomerate with pebble-sized basalt fragments. Overlying this is 20–30 m of pillow basalt in which shallow-dipping pillows are 1 m in diameter. Then there is 50–75 m of highly vesicular basalts, another 20 m of pillow basalts and then the main part of the formation, which is composed of thick flows (up to 730 m thick) of vesicular, amygdaloidal, and massive basalts (*AFkb*), some of which are plagioclase-phyric,.

Dolerite (*AF(d)*)

Fine- to coarse-grained dolerite (*AF(d)*) forms part of a sill in the Kylena Formation in the far-southeastern corner of CARLINDIE (MGA 760000E 7678250N). This dolerite retains well-preserved igneous textures and mineralogy consisting of an intergrowth of augite, plagioclase feldspar, and iron oxides. Augite is deuterically altered and chlorite and sericite are common alteration products.

Structural geology of the Fortescue Group

The Fortescue Group unconformably overlies the folded, c. 2940 Ma Lalla Rookh Sandstone of the De Grey Group. The set of folds and faults that affects these older rocks is here assigned to D_{4b} deformation. The basal Bellary Formation of the Fortescue Group was affected by gentle to open, east-northeast folds (MGA 758600E 7684700N) before deposition of the overlying Mount Roe Basalt. The style and geometry of the folds suggest that this period of deformation (D_{F1}) resulted from compression, which contrasts with the extensional stress regime commonly cited for deposition of the Fortescue Group (Blake, 1993, 2001; Thorne and Trendall, 2001).

Deposition of the Mount Roe Basalt was accompanied by east–west extension (D_{F2}; Thorne and Trendall, 2001; Bagas et al., 2003), which on CARLINDIE is manifest as normal faults along the basal contact of the formation (e.g. MGA 756500E 7680000N) and in older rocks (e.g. *AF(st)* at MGA 758500E 7684500N). On CARLINDIE there is only weak evidence that the Mount Roe Basalt was deformed before deposition of the Hardey Formation in the form of a low-angle discordance between bedding trends in the two formations. However, adjacent map sheets contain evidence for a period of strong deformation at this time, resulting in tight folding and faulting of the Mount Roe Basalt (D_{F3}; Van Kranendonk, 2000, 2003).

Deposition of the Hardey Formation was followed by another period of low-angle tilting (D_{F4}), which produced a low-angle unconformity between the Hardey and Kylena Formations on CARLINDIE. Faults also affect the Kylena Formation (D_{F5}), but the age of this deformation on CARLINDIE is unconstrained.

?Archaean to Proterozoic geology

Minor intrusive rocks (*d*, *Ᵽdw*, *Ᵽdo*, *q*)

A north-northwesterly to north-northeasterly striking swarm of fine- to medium-grained dolerite dykes (*d*) of uncertain age and affiliation cut across the western part of the Carlindie Granitoid Complex on CARLINDIE. These massive, but metamorphically recrystallized, dykes commonly lie within faults and are cut by, or pass along strike into, massive white quartz veins (*q*). In thin section the dolerite dykes consist of chlorite-altered laths of clinopyroxene within interstitial plagioclase that has been altered to sericite. The dykes contain small grains of free quartz along with hematite-altered flakes or needles of original iron oxides. Weakly deformed dykes cutting the Coonterunah Group on NORTH SHAW to the south contain fresh clinopyroxene phenocrysts and plagioclase in a groundmass of actinolite–epidote–rutile. Clinopyroxene is locally rimmed by relics of brown-green pleochroic hornblende, and then by a secondary rim of actinolite, indicating a two-stage metamorphic overprint in this area.

Two swarms of Proterozoic dolerite dykes cut through the Carlindi Granitoid Complex on CARLINDIE. One main, branching dolerite dyke that trends east-northeast is assigned to the Mundine Well dyke swarm (*Ᵽdw*; Hickman and Lipple, 1978). Tyler (1991) stated that this suite extends across the Pilbara Craton, is younger than the Bangemall Supergroup in the Bangemall Superbasin, and thus probably younger than Mesoproterozoic. A date of 755 ± 3 Ma was obtained for two dykes of the Mundine Well dyke swarm from the Bangemall Superbasin, and a Pb-loss discordia estimate based on discordant inherited zircons from a dated sample from CARLINDIE indicates a similar age of emplacement in the northern part of the Pilbara Craton (Wingate and Giddings, 2000).

The dyke belonging to the Mundine Well dyke swarm on CARLINDIE is locally a medium- to coarse-grained dolerite dyke, but is distinctive elsewhere in that it commonly contains xenoliths of variably assimilated and recrystallized granitic rocks and is flanked by metre-wide zones of potassic wall-rock alteration. Granitic xenoliths have a distinctive, coarse-grained texture defined by spherical to ovoid patches of grey quartz surrounded by pink feldspar. In thin section the granitic rocks are composed of linked, elliptical to elongate aggregates of quartz, 1–10 mm across, in a red matrix of feldspar. The quartz forms coarse, unstrained crystals with commonly sutured and sharp curved boundaries with adjacent myrmekite or feldspar. A dark-pink rind of myrmekite, typically 0.5 mm wide, surrounds the quartz. Feldspars consist of relict cores of coarse-grained plagioclase and K-feldspar rimmed by fine-grained, montmorillonite with or without hematite and myrmekite. The groundmass of the dyke where xenoliths are common is composed mainly of '…euhedral plagioclase, secondary chlorite, and abundant interstitial quartz–feldspar granophyre' with secondary amphibole, biotite, and epidote (Wingate and Giddings, 2000, p. 336).

Some of the dolerite dykes that strike east-southeast to east-northeast across the Carlindi Granitoid Complex probably belong to the Proterozoic Round Hummock suite of Hickman and Lipple (1978), herein referred to as the Round Hummock dyke swarm. The dolerite dykes of this coeval to possibly younger swarm (*Ᵽdo*) are commonly fine-grained, dark-green- to black-weathering rocks with a fine ophitic texture of plagioclase laths and interstitial augite. Some of the dykes contain a hydrous mafic mineral assemblage of actinolite and epidote intergrown with plagioclase. In these dykes, relics of pyroxenes have been completely altered to fine-grained green chlorite, sericite, and ?feldspar as a result of intense deuteric alteration. These dykes were emplaced into fractures that are filled along strike by quartz (*q*), and quartz veins commonly fill parallel fractures to some of the dykes.

White, massive vein quartz (*q*) fills fault-related fractures across many parts of CARLINDIE, and in many orientations. Many are probably Archaean in age, or at least fill Archaean structures (e.g. MGA 731600E 7685100N), but some fill north–south faults that cut Proterozoic dolerite dykes (e.g. MGA 725000E 7692500N), and thus all quartz veins have been collectively assigned to an undefined Archaean to Proterozoic age for ease of reference.

Structural geology

A set of quartz-filled faults that strike northerly across the Carlindi Granitoid Complex are parallel to the late dolerite dykes of the Round Hummock dyke swarm (*Ᵽdo*) with which they are associated. These faults apparently offset the Mundine Well dolerite dyke (*Ᵽdw*; MGA 725000E, 7692500N) and thus can be interpreted as Proterozoic structures.

Cainozoic deposits

Cainozoic deposits are widespread in the Carlindi and Pippingarra Granitoid Complexes of CARLINDIE and sparsely distributed in areas of greenstones. Older deposits include consolidated alluvial, colluvial, and residual material. More-recent unconsolidated Quaternary deposits include alluvial, colluvial, and eluvial material.

Alluvial deposits (*Cza*, *Czak*)

Medium-grained, weakly consolidated to unlithified alluvial deposits along the banks of the Shaw River and Six Mile Creek (*Cza*) consist of medium-grained, dominantly quartz–feldspar and chert sand with local clay cement, which has been dissected by Quaternary drainage and overlain by Quaternary overbank deposits (*Qao*).

Massive, nodular and cavernous calcrete, of alluvial origin (*Czak*), has locally formed along old drainage channels in the western part of CARLINDIE.

Colluvial deposits (*Czc*, *Czcg*, *Czcf*)

Consolidated, dissected colluvium (*Czc*) is derived from adjacent rock outcrops through erosion of topographically high greenstones. Composed of clay, silt, sand, and pebbly sand and gravel with clay or silica cement, dissected colluvium (*Czc*) is most widely distributed on low slopes washing off greenstone belts in the southeast of CARLINDIE. Variably consolidated and dissected colluvium derived from granitic rocks (*Czcg*) is composed of quartz–feldspar clay, silt, sand, and gravel on low-gradient outwash fans. Ferruginous colluvium (*Czcf*) is deposited downslope from high hills of banded iron-formation and consists of dark-brown-weathering gravel, sand, and silt derived from the iron-rich sedimentary rocks and some minor laterite. Iron-rich, consolidated deposits (colluvium and/or alluvium) outcrop in small areas on the flanks of large river systems where they have been exposed and eroded by recent drainage (Fig. 30). These deposits probably

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Figure 30. Small outcrop of residual, ferruginous Cainozoic alluvium or colluvium overlying leucogranite diatexite of the Carlindi Granitoid Complex (*AgLlxn*) on the bank of the Strelley River West (MGA 719600E 7719000N). These deposits are too small to show on the map, but probably underlie a large area of Quaternary sheetwash (*Qwg*)

underlie a large area of Quaternary sheetwash deposits of sand and quartz pebbles overlying, and derived from, granitic rocks (*Qwg*).

Residual deposits (*Czrg, Czrk*)

Consolidated and dissected mixed eluvium and colluvium is composed of quartz–feldspar clay, silt, sand, and gravel derived from granitic rocks (*Czrg*). Residual calcrete (*Czrk*) overlies, and is derived from, altered carbonate-rich ultramafic rocks (MGA 712000E 7677500N) and granitic rocks over large areas bordering rivers or creeks in the southern half of CARLINDIE. The calcrete formed as sheets, encrustations, and joint-fills, and is either massive or nodular, white, fine-grained calcium carbonate in irregular deposits probably up to a few metres thick.

Quaternary sheetwash, colluvial, residual and eolian deposits (*Qw, Qwg, Qc, Qcq, Qs, Qrg*)

Low-gradient sheetwash deposits occupy large areas of CARLINDIE, representing the northward transport of detritus from greenstone belts in the south towards the Indian Ocean as the result of seasonal annual flooding associated with cyclonic rains. Sheetwash with mixed protolith (*Qw*) is designated separately from sheetwash deposits of quartz and feldspar sand and gravelly pebbles (*Qwg*) that are derived from, and overlie, large areas of granitic rock on CARLINDIE.

Recent colluvium consisting of sand, silt, and gravel (*Qc*) forms outwash fans, scree, and talus, and is common in hilly areas and on the surface of the granitic complex. A specific colluvial unit adjacent to vein quartz (*q*) consists of white quartz sand and pebbles on talus aprons around quartz ridges (*Qcq*).

Fine- to medium-grained, red to bright-orange eolian sand (*Qs*) forms undulating sheets along the southern edge of the map. The variable grain size and coarser grained components of these sands suggest that they constitute a mixture of eolian and eluvial sand.

Medium- to coarse-grained, residual quartz and feldspar sand with scattered quartz pebbles and granite fragments (*Qrg*) overlies, or is adjacent to, the main granitic exposures. Although the unit is mainly residual, there is some reworking of the finer components by water and wind action.

Quaternary lacustrine deposits (*Qlb*)

Small (~1 km^2) lake deposits (e.g. MGA 744300E 7681000N) in between large rivers and creeks consist of fine grey to black silt and mud with a crabhole surface (*Qlb*) that may have holes up to 30 cm deep. These do not commonly contain standing water, except immediately after flooding events associated with cyclones.

Quaternary alluvial deposits (*Qaas, Qao, Qaoc, Qaob, Qaa*)

The creek and river system on CARLINDIE contains a wide range of alluvial deposits. The major drainage channels are occupied by unconsolidated sand, gravel, and silt (minor clay; *Qaas*) that are reshaped every year by strong flow during cyclones. The surface of the major channels is incised below the top of adjacent floodplains and overbank of alluvial sand and silt, with minor clay, and gravel (*Qao*). Large areas of alluvial silt, clay, and minor sand with numerous small claypans (*Qaoc*) are developed on floodplains. Larger areas of overbank deposits on floodplains contain light reddish-brown to grey or white clay, with local crabhole surfaces (*Qaob*).

Unconsolidated alluvial sand, silt, gravel, and minor clay (*Qaa*) occupy small- to medium-sized creeks and rivers and smaller channels on floodplains. This also commonly includes subordinate amounts of overbank deposits (*Qao*) and sheetwash sand and gravel (*Qw*) in small drainage systems. Minor drainage channels commonly have a clay surface, although some have a scattered quartz-pebble or rock-fragment veneer.

Geochronology

Samples of volcanic rocks and clastic and volcaniclastic sedimentary rocks from CARLINDIE were collected for U–Pb dating of zircons using the SHRIMP II facility at Curtin University. The results are published in GSWA Records as indicated below. A summary of these results are presented in the following section in chronologic order from oldest to youngest, and in Table 2 and Figure 31.

Coucal Formation, Coonterunah Group (GSWA 168995)

The stratigraphically oldest rock that was dated on CARLINDIE is a sample of massive, fine-grained rhyolite with quartz phenocrysts (*AOcfr*) that was collected from near the intrusive contact with the Carlindi Granitoid Complex along the northwestern edge of the Warralong greenstone belt (GSWA 168995 at MGA 755210E 7694250N; Nelson, 2002). The unit belongs to the top of the interpreted extrusive component of the Coucal Formation of the Coonterunah Group. Results indicate a main population of 14 zircons at 3498 ± 2 Ma, and several more highly discordant zircons with younger $^{207}Pb/^{206}Pb$ ages that are interpreted as the result of Pb-loss during younger disturbance events. However, a worrying feature of the data is that the 3498 ± 2 Ma age of the rock is identical to xenocrystic populations in many other samples from CARLINDIE (Fig. 31), as described below, and the description of the zircons includes some that are rounded and pitted and of detrital origin (Nelson, 2002). Furthermore, some of the least discordant zircons with younger $^{207}Pb/^{206}Pb$ ages give results that are in the range of well dated igneous events throughout the East Pilbara Granite–Greenstone, namely the age of either the Panorama or Duffer Formations at c. 3460 Ma. Thus,

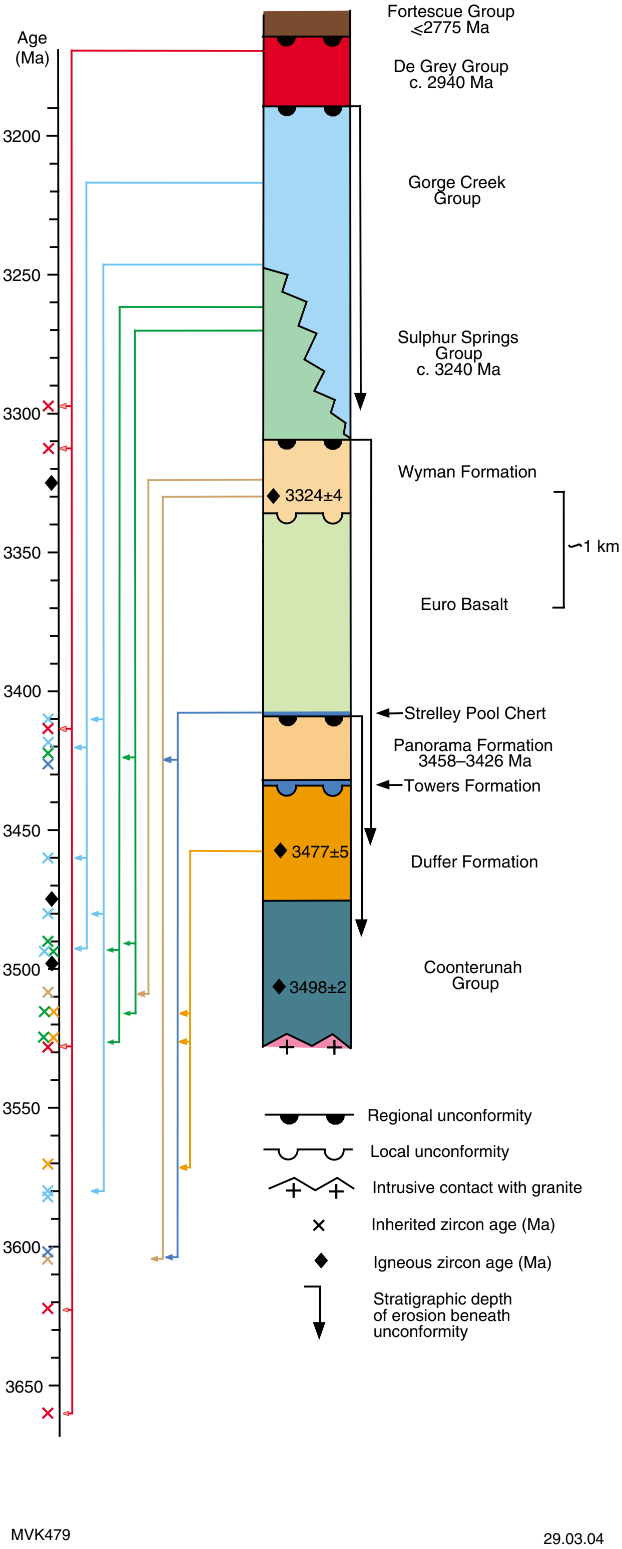

Figure 31. Time line and schematic stratigraphic column of the Warralong greenstone belt, showing relations between igneous ages and inherited zircon data from samples collected on CARLINDIE and immediately adjacent sheet areas

although the rock is herein interpreted to be part of the Coucal Formation of the Coonterunah Group, another interpretation is that this rock is part of a younger formation that has only inherited zircons. Further dating and geochemistry will be required to discriminate between these two possibilities.

Duffer Formation, Warrawoona Group (GSWA 168996)

A sample of massive to well bedded, quartz-phenocrystic, crystal–lithic felsic tuffaceous sandstone (GSWA 168996 at MGA 759540E 7693420N; Nelson, 2002) is from what is interpreted from mapping as part of the Duffer Formation (*AWdstv*). The sample yielded zircon age populations at 3571 ± 6 Ma (6 zircons), 3524 ± 4 Ma (2 zircons), and 3477 ± 5 Ma (9 zircons), the latter indicating a maximum age of deposition of the rock. The 3477 ± 5 Ma age of the youngest population is within error of the oldest age from the Duffer Formation in the type area in the Marble Bar greenstone belt (3474 ± 7 Ma; Nelson, 2000). The older populations are interpreted to be xenocrystic zircons from unknown sources (Table 2, Fig. 31).

Strelley Pool Chert, Warrawoona Group (GSWA 142836)

A sample of thickly bedded, white, quartz-rich sandstone with detrital quartz and lithic fragments (minor) was collected from the Strelley Pool Chert (*AWsstq*) on COONGAN (GSWA 142836 at MGA 758720E 7692270N; Nelson, 1998), just 200 m east of the eastern boundary of CARLINDIE. The sample yielded rounded zircons, characteristic of detrital transport, that fall into two age populations at 3602 ± 5 Ma (24 zircons) and 3426 ± 10 Ma (7 zircons).

Euro Basalt, Warrawoona Group (GSWA 168994)

A sample of thinly bedded, fine-grained felsic tuff from within the Euro Basalt (*AWeft*; GSWA 168994 at MGA 756300E 7690920N) yielded only zircons of Fortescue Group age, indicating zircon crystallization from low-temperature hydrothermal fluids (Nelson, D. R., written comm., 2001).

Wyman Formation, Warrawoona Group (GSWA 168993 and 168992)

Two samples of quartz-rich clastic sedimentary rocks from the Wyman Formation of the Warrawoona Group (*AWwstq*) were collected for U–Pb zircon geochronology on CARLINDIE. The two samples are within about 400 m of each other where the formation lies with erosional disconformity on the Euro Basalt (near MGA 751750E 7689400N; see Fig. 10 and **Wyman Formation**). One sample (GSWA 168993) of clean white quartzite from higher up in the unit yielded a single zircon population (30 grains) at 3508 ± 3 Ma (Nelson, 2002), which is interpreted as an inherited detrital population. The other sample (GSWA 168992) from lower in the succession is a granule sandstone with nearly 100% clasts of black to grey hydrothermal chert (Fig. 11) derived from a swarm of synsedimentary hydrothermal chert veins that cut through the immediately underlying, altered basaltic rocks of the Euro Basalt (see Fig. 10 and **Wyman Formation**). The sandstone yielded a dominant population of zircons at 3324 ± 4 Ma and another at 3603 ± 5 Ma. The older-than-3500 Ma zircon populations in these two samples are interpreted as inherited components from an ancient, unrecognized basement. However, the population of 3324 ± 4 Ma zircons in the sandstone dominated by hydrothermal chert is the same age as several rhyodacite samples of the Wyman Formation elsewhere in the EPGGT (Thorpe et al., 1992a; McNaughton et al., 1993; Buick et al., 2002; Nelson, 2001), and is interpreted to indicate the depositional age of the sediment.

Sulphur Springs Group (GSWA 168989 and 168991)

Two samples from felsic volcaniclastic rocks of the Sulphur Springs Group that unconformably overlie the Wyman Formation have been dated (GSWA 168989 and 168991; Nelson, 2002). GSWA 168989 (MGA 747810E 7685040N) is of a 50 cm-thick, white, quartz-rich sandstone lens within felsic volcaniclastic rocks and volcaniclastic conglomerate (part of *ASksc*) and yielded three zircon populations at 3514 ± 7 Ma (6 zircons), 3491 ± 4 Ma (19 zircons), and 3423 ± 8 Ma (5 zircons). GSWA 168991 (MGA 749170E 7687070N) is a massive, quartz-crystal-bearing felsic volcaniclastic rock (*AScsv*) with chert fragments (to 2 cm) and altered biotite crystals. This sample returned zircon populations at 3496 ± 4 Ma (19 zircons) and 3524 ± 10 Ma (1 zircon). All the zircons populations from these two samples are interpreted to be inherited, as the rocks show clearly unconformable relationships on stratigraphically older rocks of the Warrawoona Group that are as young as c. 3324 Ma (see Wyman Formation sample GSWA 168992 above).

Carlindi Granitoid Complex (*AgLmh*; GSWA 178040)

Strongly foliated biotite monzogranite (*AgLmh*) sampled from the bed of Strelley River East (MGA 734600E 7698100N) in the Carlindi Granitoid Complex yielded a single population of 17 zircons with a pooled mean age of 3252 ± 4 Ma, which is interpreted to be the igneous age of the monzogranite (Nelson, in prep.b).

Gorge Creek Group (GSWA 168997 and 168990)

GSWA 168997 contains quartz-rich sandstone from the Corboy Formation of the Gorge Creek Group (*AGcstq*) from about 2 km east of the edge of the map sheet on COONGAN (Van Kranendonk, 2004) and yielded a dominant zircon population at 3410 ± 6 Ma (24 zircons), and single zircon ages of 3481 ± 20 and 3582 ± 13 Ma (Nelson, 2002). The 3410 Ma zircon age group provides a maximum age of deposition of the sediment, which is probably younger than 3235 Ma based on geological relationships and geochronology from NORTH SHAW (Van Kranendonk, 2000; Buick et al., 2002).

Sample GSWA 168990 of thickly bedded grey quartz-rich sandstone (*AGpstq*) from the Paddy Market Formation of the Gorge Creek Group (MGA 748010E 7684310N) yielded a main population of zircons at 3496 ± 2 Ma (27 zircons), one zircon at 3459 ± 7 Ma, and one zircon at 3419 ± 12 Ma (Nelson, 2002). These zircons are interpreted to be detrital in origin, and thus provide useful age information about the eroded source region, but not in regard to the depositional age of the sediment.

Carlindi Granitoid Complex (*AgLmm*; GSWA 160745)

Strongly foliated to mylonitic biotite granodiorite of the Carlindi Granitoid Complex (*AgLmm*; GSWA 160745; Nelson, 2001) from within the eastern margin of the Tabba Tabba Shear Zone (MGA 709790E 7727360N) returned an igneous crystallization age of 2940 ± 3 Ma, providing a maximum age of an episode of sinistral shear deformation within the zone. This sample also contained inherited zircons at 3326 ± 7 Ma (1 zircon), 3248 ± 12 Ma (3 zircons), and 3518 ± 11 Ma (3 zircons; Nelson, 2001), ages that are well known as major magmatic events throughout the EPGGT (e.g. Van Kranendonk et al., 2002).

Mundine Well dyke swarm (B20)

A sample of crustally contaminated dolerite of the Mundine Well dyke swarm (B20) contained numerous inherited zircons, with age populations as shown on Table 2 (Wingate and Giddings, 2000). Eight of the youngest zircon age results pool to give a mean age of 2859 ± 2 Ma (Wingate, M. T. D., University of Western Australia, written comm., 2003 from data published in Wingate and Giddings, 2000), which is interpreted to indicate the age of the Kadgewarrina Monzogranite (*AgLkd*) that hosts the dolerite dyke.

Discussion

Zircon age data from the dated samples on CARLINDIE indicate the presence of inherited or detrital zircons derived from ancient crust during deposition of the Pilbara Supergroup (Fig. 31). In addition to samples from the Sulphur Springs and Gorge Creek Groups that have inheritance from older exposed parts of the stratigraphy, two significant periods of older crust formation are indicated that were derived from a source region that is now unexposed, eroded away, or undiscovered: one at 3530–3490 Ma, and another at 3660–3570 Ma. The first period of older crust formation overlaps with and extends slightly beyond the known age of the lowermost parts of the Warrawoona Group (c. 3490 Ma: Thorpe et al., 1992b; van Koolwijk et al., 2001) and the Coonterunah Group (3515–3498 Ma), whereas the second is much older and correlates with similar ages from inherited zircons in samples collected from elsewhere in the EPGGT (McNaughton et al., 1988; Williams, 1999). Zircons from this source region are also in Warrawoona Group samples, indicating the presence of widespread older crust during Pilbara Supergroup deposition (Van Kranendonk et al., 2002). Zircons from successively younger groups commonly contain older populations of zircons, in addition to the expected younger populations of inherited zircons (Fig. 31). This is interpreted to reflect progressive exhumation of deeper, older levels of the crust in the cores of granitic domes during punctuated episodes of partial convective overturn of the crust (Collins et al., 1998; Van Kranendonk et al., 2002).

Economic geology

Beryl, tantalum, tin, mica

Several small workings of pegmatite-hosted beryl, tantalum, and tin are associated with the post-tectonic, c. 2860 Ma Kadgewarrina Monzogranite (*AgLkd*) of the Carlindi Granitoid Complex on CARLINDIE. The largest of these is the Strelley mine (tantalum–beryl–tin; WAMIN* point 3100 on the map), which mined idiomorphic beryl crystals up to 10 cm long in an 800 × 200 m muscovite pegmatite in foliated granite in the Tabba Tabba Shear Zone. Tantalum workings, including pits and shafts, were developed over a length of 400 m. Mining commenced in 1928 with 5790.65 t of Ta_2O_5 recorded, and then from 1953 till 1961 when 434.65 kg beryl was mined (Ferguson and Ruddock, 2001).

Other workings include the Biscay Well 1 (beryl–tantalum; WAMIN point 6047), Biscay Well 2 (mica–beryl; WAMIN point 6048), Turkey Camp Well (beryl; WAMIN point 3101), and Kaylen Well (tantalum; WAMIN point 6045). All of these represent minor development of pegmatite-hosted ore. Large green beryl and muscovite crystals can still be observed in situ in pegmatite at Turkey Camp Well. Alluvial cassiterite was extracted from Crawford Bore (tin; WAMIN point 7895) near the head of the Strelley River West (MGA 711750E 7696000N) in the Kadgewarrina Monzogranite.

Barite

Multiple occurrences of vein barite and units of baritic sandstone have been recorded from the Miralga Creek area in the southern part of the Warralong greenstone belt, 4–8 km north-northeast of Cooke Bluff Hill (Hickman, 1977b). These occurrences have been summarized in the WAMIN database as four deposits, labelled Cooke Bluff Hill 1 and 2 and Miralga Creek 3 and 4 (WAMIN points 6039 to 6042; Ferguson and Ruddock, 2001). Hickman (1977b) provided detailed maps of the occurrences and geochemical analyses of the barite veins and baritic sandstone, which outcrop near and are hosted by rocks of the Euro Basalt and Sulphur Springs Group. Barite veins contain grey, coarsely crystalline, isopachous barite with crystals up to 10–15 cm. Barite veins reach a maximum of 10 m in width and may extend over hundreds of metres in length along planar to irregular veins. The main baritic sandstone unit corresponds to the basal Leilira Formation of the Sulphur Springs Group along the unconformity on the Euro Basalt. The main concentration of veins is stratigraphically underneath this unit, to the north (Hickman, 1977b). Hickman (1977b) estimated a total inferred barite resource in the Miralga Creek area of about 67 000 tonnes. Samples of barite veins, barite sandstone, associated gossan, and soils were analysed for lead, copper, zinc, gold, and silver, but no anomalous values of these metals were recorded (Hickman, 1977b).

The veins and baritic sandstone in the core of the Warralong Syncline in this area are concentrated around a zone of strong north–south faulting, which is interpreted here to represent a fluid pathway during hydrothermal fluid circulation (see Fig. 13). Hydrothermal circulation is interpreted to have occurred during Sulphur Springs Group volcanism because the veins are present up to and within the lowermost parts of the Sulphur Springs Group. Barite in the basal baritic sandstone of the Leilira Formation (*ASlstq*) is interpreted as secondary cement that formed together with silica cement during hydrothermal chert–barite veining.

Gold

A single anomalous occurrence of gold was documented by Hickman and Gibson (1981) in a thin conglomerate horizon in the basal Bellary Formation of the Fortescue Group (MGA 756750E 7681100N). This anomaly, known as Contact Creek (WAMIN point 7459) consists of a single anomalous chip sample from gossan in conglomerate, which contained up to 4.8 g/t Au, and 39 ppm Sb. In a diamond drillhole 250 m south of the site, 1.38 g/t Au was intersected over 0.58 m (between 8.82 and 9.4 m) in a thin unit of conglomerate.

Industrial mineral: chert

Chert is a widespread rock type throughout the Warralong greenstone belt, and three narrow ridges near the Marble Bar – Port Hedland Highway were investigated for their purity by Abeysinghe (2003), who found that they were of high quality, with an average of five analysed samples being 98.44% SiO_2. These are listed as WAMIN points 7813, 7814, and 7817 (all within 500 m of where the symbol is placed on the map at MGA 759500E 7696500N).

* From the GSWA's Western Australian mineral occurrence (WAMIN) database.

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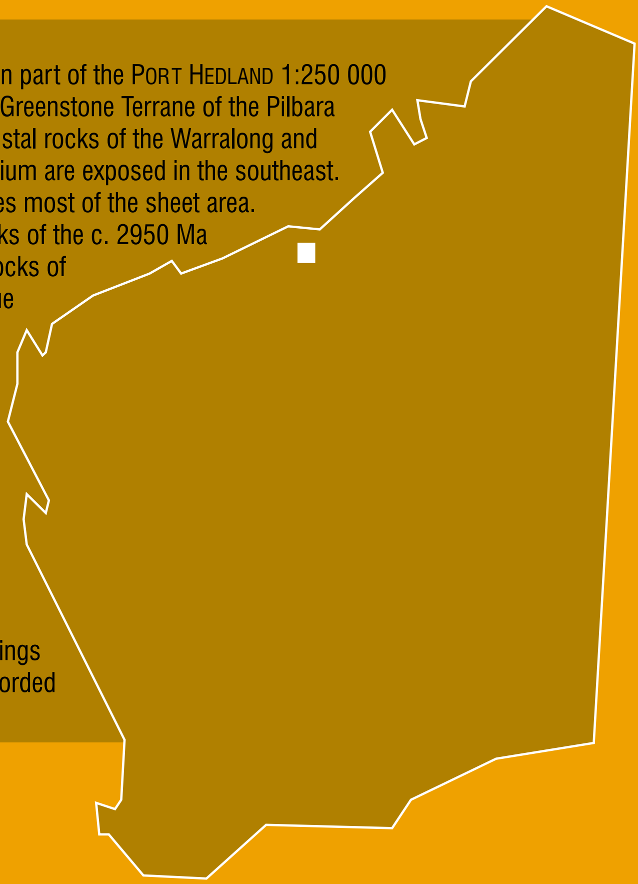
Appendix

Gazetteer of localities

Locality	MGA coordinates Easting	Northing
Biscay Well 1 (beryl and tantalum occurrence)	720720	7704150
Biscay Well 2 (mica and beryl occurrence)	719720	7704150
Carlindie Hill	718990	7712260
Crawford Bore	711750	7696000
Contact Creek (gold occurrence)	756750	7681100
Cooke Bluff Hill	746050	7681360
Cooke Bluff Hill 1 (barite locality)	747250	7683850
Cooke Bluff Hill 2 (barite locality)	747920	7685300
Kaylen Well (tantalum occurrence)	717150	7697300
Kimmys Bore	713400	7686450
Lalla Rookh Homestead (abandoned)	722500	7689300
Miralga Creek 3 (barite locality)	750880	7688280
Miralga Creek 4 (barite locality)	751720	7689600
No. 8 well	759400	7702800
Red Rock Creek	714710	7719950
Strelley Mine (tantalum, beryl, tin)	709800	7728000
Turkey Camp Well (beryl occurrence)	717790	7698960

The CARLINDIE 1:100 000 sheet covers the central-southern part of the PORT HEDLAND 1:250 000 sheet in the north-central part of the East Pilbara Granite–Greenstone Terrane of the Pilbara Craton. Archaean (c. 3500–2940 Ma) basement supracrustal rocks of the Warralong and Panorama greenstone belts and the Lalla Rookh Synclinorium are exposed in the southeast. The c. 3475–2860 Ma Carlindi Granitoid Complex occupies most of the sheet area. Metagabbros, ultramafic rocks, and metasedimentary rocks of the c. 2950 Ma Tabba Tabba Shear Zone are unconformably overlain by rocks of the Mount Bruce Supergroup (c. 2775–2741 Ma Fortescue Group) in the Marble Bar Sub-basin of the Hamersley Basin. The structural history of the area — identified by crosscutting relationships between units, structures, and unconformities — includes several periods of basin subsidence and granite doming from 3470 to 2740 Ma, and sinistral transpression at c. 2940 Ma. Beryl–tantalum–tin–mica mineralization is associated with the c. 2860 Ma Kadgewarrina Monzogranite and pegmatite in the Tabba Tabba Shear Zone. Hydrothermal barite veins cutting the Warralong greenstone belt are associated with deposition of the c. 3240 Ma Sulphur Springs Group. A single anomalous gold occurrence has been recorded from the basal unconformity of the Fortescue Group.



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VAN KRANENDONK

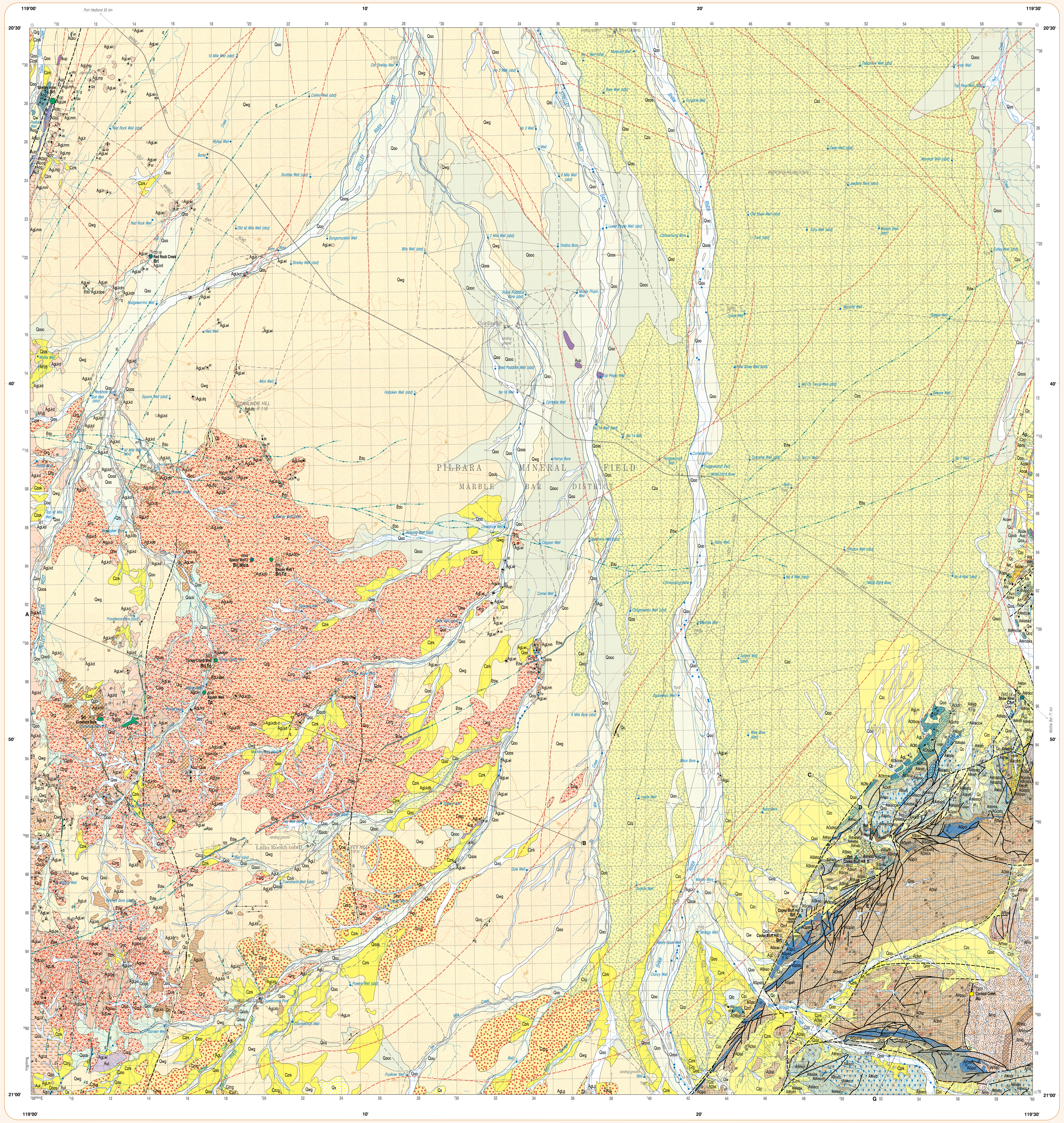
Geology of the Carlindie 1:100 000 sheet

EXPLANATORY NOTES

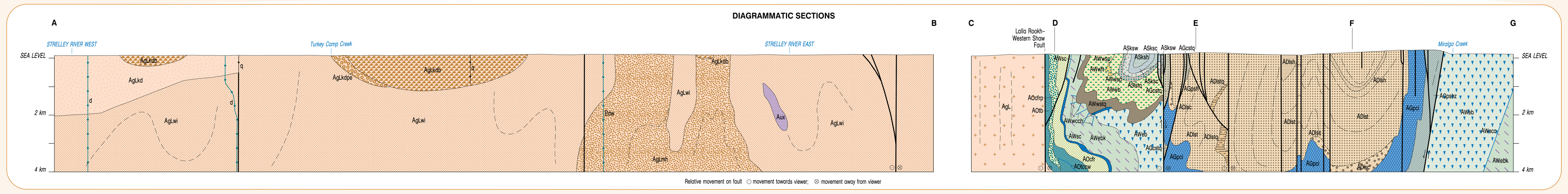
CARLINDIE

GEOLOGICAL SURVEY OF WESTERN AUSTRALIA

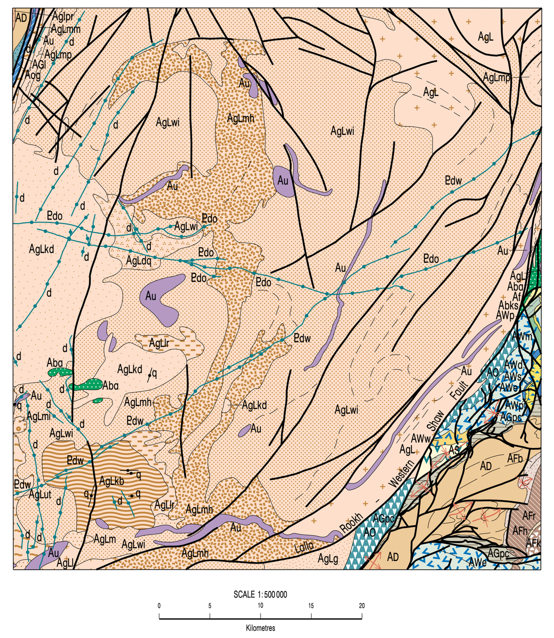
SHEET 2756



DIAGRAMMATIC SECTIONS



INTERPRETED BEDROCK GEOLOGY



For further details, refer to main reference

MINERAL OCCURRENCES

MINERALIZATION STYLES*

- Porphyry, pegmatite, greisen, and skarn
- Stratabound volcanic and sedimentary
- Stratabound sedimentary and/or sedimentary banded iron-formation
- Regolith hosted

MINERAL AND ROCK COMMODITY GROUPS

- Precious metal
- Speciality metal
- Industrial mineral

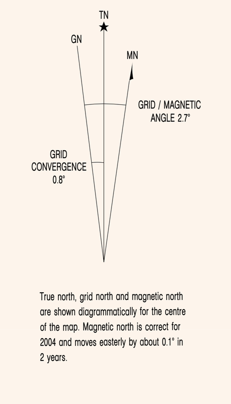
MINERAL AND ROCK COMMODITIES

Barite	Brt
Beryl	Brl
Chert	Chrt
Gold	Au
Mica	Mica
Tantalum	Ta
Tin (cassiterite)	Sn

OPERATING STATUS AND SITE IDENTIFICATION NUMBER

Abandoned mine	e.g. 3100
Mineral deposit	e.g. 7895
Mineral occurrence or prospect	e.g. 7459

Mineral occurrences and numbers are from the GSWA WAMIN database.
*Larger symbols represent mines or deposits also in the DoIR MINEDEX database.



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Geochronology by:

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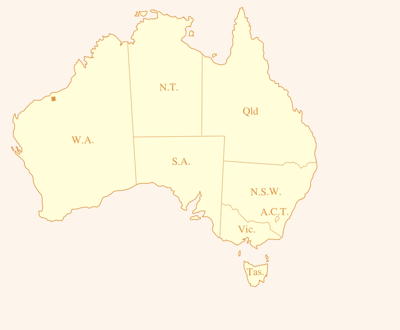
Theme	Data Source	Data Currency	Agency
Geology	GSWA	2000–2002	Dept of Industry and Resources
Structural data	WAROX	FEB 2003	Dept of Industry and Resources
Mineral occurrences (non-confidential)	MINDEX	SEPT 2003	Dept of Industry and Resources
	WAMIN	SEPT 2003	Dept of Industry and Resources
Control	GESMAR	JUNE 2002	Dept of Land Information
Topographic nomenclature	GEONOMA	JUNE 2002	Dept of Land Information
Topography	DLI and GSWA field survey	APR 2002	Dept of Land Information
Water exploration bores	AQWA (WRC)	AUG 2003	Dept of Enviromental Protection



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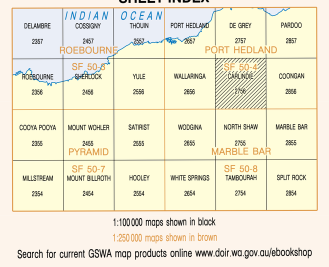

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SCALE 1:100 000

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 50

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

CARLINDIE

SHEET 2756 FIRST EDITION 2004
Version 1.0 — May 2004