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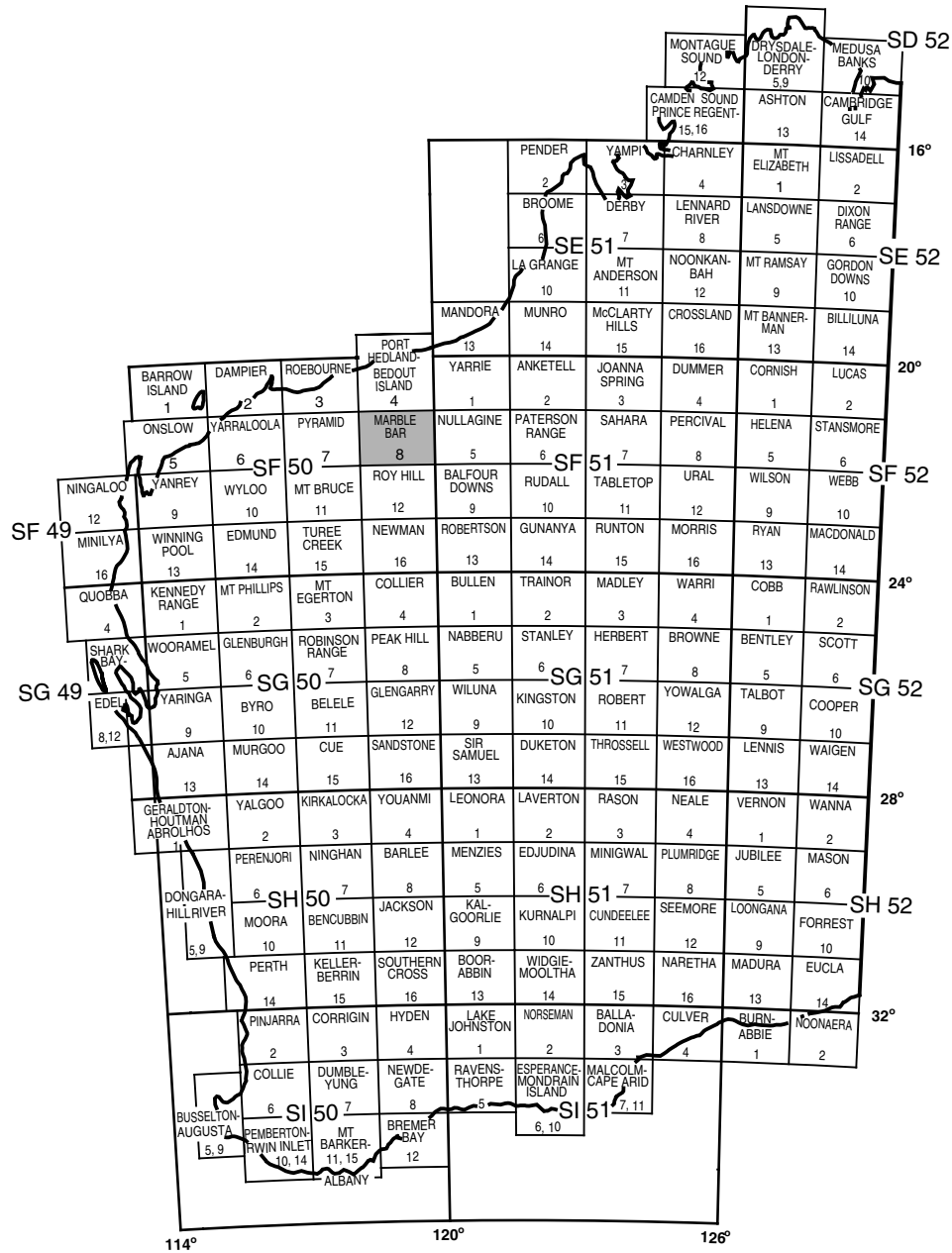
# **GEOLOGY OF THE WHITE SPRINGS 1:100 000 SHEET**

by R. H. Smithies

**1:100 000 GEOLOGICAL SERIES**



**Geological Survey of Western Australia**



|                          |                    |                    |
|--------------------------|--------------------|--------------------|
| WODGINA<br>2655          | NORTH SHAW<br>2755 | MARBLE BAR<br>2855 |
| WHITE<br>SPRINGS<br>2654 | TAMBOURAH<br>2754  | SPLIT ROCK<br>2854 |



**GEOLOGICAL SURVEY OF WESTERN AUSTRALIA**

**GEOLOGY OF THE  
WHITE SPRINGS  
1:100 000 SHEET**

**by  
R. H. Smithies**

**Perth 2003**

**MINISTER FOR STATE DEVELOPMENT**  
**Hon Clive Brown MLA**

**DIRECTOR GENERAL, DEPARTMENT OF INDUSTRY AND RESOURCES**  
**Jim Limerick**

**DIRECTOR, GEOLOGICAL SURVEY OF WESTERN AUSTRALIA**  
**Tim Griffin**

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**Cover photograph:**

View from the southwestern part of WHITE SPRINGS looking north over the Chichester Range



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# Geology of the White Springs 1:100 000 sheet

by

R. H. Smithies

## Abstract

The WHITE SPRINGS 1:100 000 sheet lies in the southwestern part of the Archaean East Pilbara Granite–Greenstone Terrane of the Pilbara Craton. The East Pilbara Granite–Greenstone Terrane is represented by the Yule Granitoid Complex, consisting of numerous generations of granitic rocks with ages between c. 3420 and 2927 Ma. The most extensively outcropping granite is schlieric biotite leucogranite of the Cockeraga Leucogranite, which dominates the central part of WHITE SPRINGS. The leucogranite is dated at younger than 3065 Ma and is interpreted to not have migrated far from its source of melting. Greenstones outcrop only as xenoliths, including roof pendants, in the rocks of the Yule Granitoid Complex, and their stratigraphic position within the greenstone succession of the East Pilbara Granite–Greenstone Terrane is unclear. These supracrustal rocks have been metamorphosed to at least lower amphibolite facies, but are now typically strongly retrogressed. There are abundant greenstone xenoliths, including roof pendants, in the ‘Mount Gratwick xenolith field’, in the centre of the sheet area, and the ‘Western Shaw greenstone belt extension’, which is a northeast-trending train of roof pendants in the southwestern part of the sheet area.

A younger component of the Pilbara Craton, the Hamersley Basin, is represented by rocks of the late Archaean Fortescue Group, which cover the southwestern part of the map sheet. The Fortescue Group unconformably overlies the East Pilbara Granite–Greenstone Terrane, and consists of shallowly dipping and weakly metamorphosed volcanic and sedimentary rocks.

**KEYWORDS:** Archaean, Pilbara Craton, regional geology, East Pilbara Granite–Greenstone Terrane.

## Introduction

The WHITE SPRINGS\* 1:100 000 geological sheet (SF 50-8, 2654) covers the southwestern part of the MARBLE BAR 1:250 000 map sheet, in the central Pilbara region (Fig. 1). It is bound by latitudes 21°30'S and 22°00'S, and longitudes 118°30'E and 119°00'E, and straddles the boundary between the West Pilbara Mineral Field and the Marble Bar District of the Pilbara Mineral Field.

Rocks are well exposed throughout the southern and northeastern parts of WHITE SPRINGS, but elsewhere form discontinuous to sparse outcrop. Most outcrop forms part of a granite–greenstone succession. However, outcrop in the southwestern and far southern parts of the sheet is predominantly of the volcano-sedimentary sequence of the Fortescue Group (see interpreted bedrock geology figure on the map), which forms the lower to middle

part of the late Archaean to Proterozoic Hamersley Basin. This sequence dips gently to the south, locally exposing the middle portion of the Fortescue Group stratigraphy.

Granite volumetrically dominates outcrop. All granites belong to the Yule Granitoid Complex, and the majority are younger than the greenstones, with ages between c. 2930 and c. 2945 Ma (Nelson, 2002). However, on the eastern side of WHITE SPRINGS, gneissic components of the granitic complex are as old as c. 3420 Ma, and their protoliths may have intruded before deposition of all the greenstones.

The greenstones on WHITE SPRINGS are assigned to the Pilbara Supergroup (Hickman, 1983), but cannot be confidently assigned to any particular group. These rocks are preserved as centimetre- to kilometre-sized xenoliths and roof pendants, either scattered throughout the Yule Granitoid Complex or locally forming discontinuous trains or zones (see interpreted bedrock geology figure). The linearity of these zones reflects the preservation of greenstones both within synclinal keels between granitoid

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

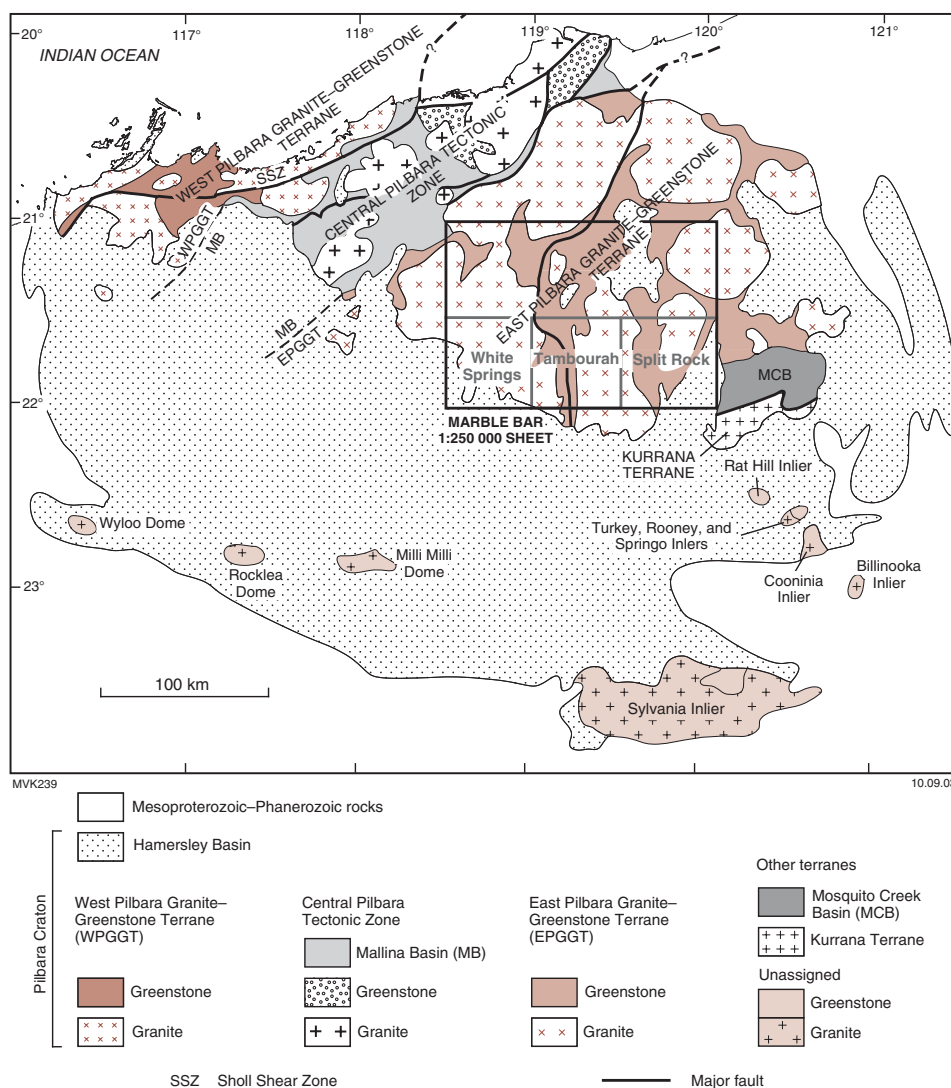


Figure 1. Regional geological setting of WHITE SPRINGS

domes and along faults. The greenstones are dominated by metamorphosed mafic igneous rocks, but with rocks derived from sedimentary and ultramafic igneous protoliths in places. All these rocks have been metamorphosed to lower amphibolite facies.

## Access and land use

The Great Northern Highway bisects WHITE SPRINGS in a northerly direction, and an unsealed road that services the Port Hedland – Mount Newman Railway runs in a similar direction through the eastern part of the sheet (Fig. 2). Both roads lead to Port Hedland, which lies about 130 km to the north. The unsealed Woodstock – Marble Bar Road connects Marble Bar to the east with the Great Northern Highway, and passes through Woodstock Homestead in the northeastern part of WHITE SPRINGS. Most of WHITE SPRINGS is only accessible by four-wheel drive vehicle on unmaintained tracks. In the southwest, most parts of the Mungaroona and Chichester Ranges are accessible only on foot or by helicopter. Woodstock Homestead is currently

inhabited and Yandearra Outstation, in the northwest, is periodically occupied. White Springs Homestead is abandoned.

The Mungaroona Range Wildlife Sanctuary occupies an area on the western side of WHITE SPRINGS. The remaining land is divided between the Mugarinya Aboriginal Community (Yandearra Station) in the west and central part, and Woodstock Station in the east. Grazing is the sole agricultural activity. There are no active mines.

## Climate and vegetation

The climate of WHITE SPRINGS is arid with an average annual rainfall of 316 mm, most of which is summer rainfall relating to thunderstorms or decaying tropical cyclones. Mean summer maximum temperatures are in the high 30s to low 40s (°C); the winters are mild, with mean minimum July temperatures of about 10°C.

WHITE SPRINGS lies within the Fortescue Botanical District, and is broadly divisible into three regimes (Beard,

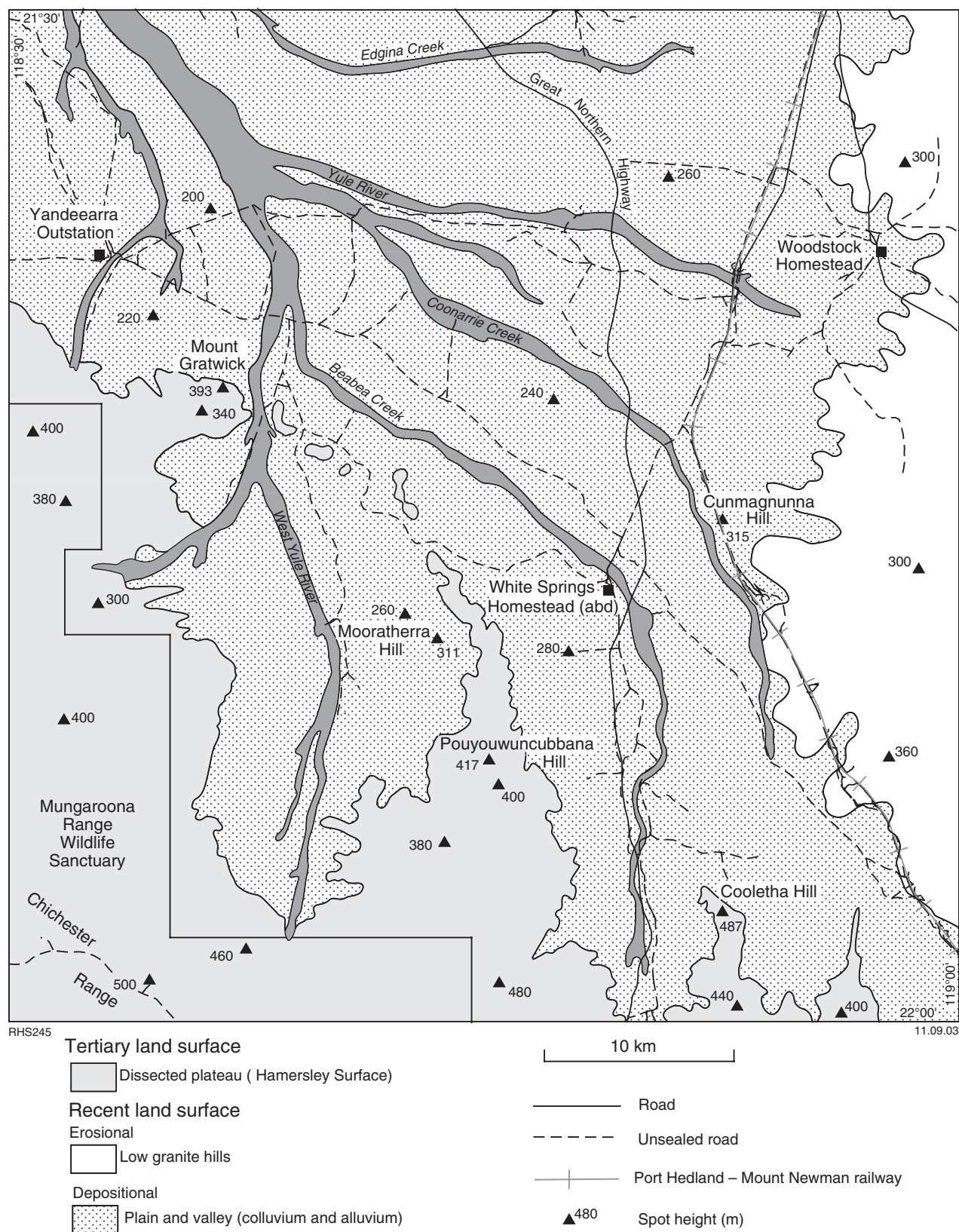


Figure 2. Physiographic features of WHITE SPRINGS



1975). The main channel and associated floodplains of the Yule River and the larger creeks are lined with riverain Sclerophyll woodlands of River Gum (*Eucalyptus camaldulensis*). The most widespread regime consists of shrub steppe of soft spinifex (*Triodia pungens*) with scattered *Acacia*, *Grevillia*, and *Hakea* species, mainly on the large granitic complexes. The third regime is a tree steppe of Snappy Gum (*Eucalyptus brevifolia*) with spinifex, and scattered *Acacia*, *Grevillia*, and *Hakea* species, restricted to hills and ranges.

## Physiography

The headwaters of the Yule River form a fan of north- to west-draining tributaries that converge to a main channel in the northwestern corner of WHITE SPRINGS (Fig. 2). This river system flows mainly during the summer wet season. Physiographic divisions on WHITE SPRINGS closely match major geological divisions. Rocks of the Fortescue Group in the southwestern quadrant of the sheet form a prominent dissected plateau (Fig. 2). This surface is up to about 500 m above sea level and is the peneplain that Campana et al. (1964) called the Hamersley Surface. Areas underlain by granitic rocks typically consist of the alluvial–colluvial plains division, except along the eastern edge of WHITE SPRINGS, where granites form low-lying hills (Fig. 2).

## Regional geological setting and previous investigations

The Pilbara Craton represents the oldest exposed major crustal element of Australia. The Archaean rocks can be divided into two components (Fig. 1): a granite–greenstone terrane that formed between c. 3600 and c. 2800 Ma (Hickman, 1983, 1990; Barley, 1997), and the unconformably overlying volcano–sedimentary sequences (Mount Bruce Supergroup) of the c. 2770 to 2300 Ma Hamersley Basin (Arndt et al., 1991). The granite–greenstone terrane of the Pilbara Craton is exposed mainly in the north and northeast of the craton where erosion has removed all but local remnants of the Mount Bruce Supergroup.

Hickman (1983) provided a comprehensive interpretation of the geological evolution of the granite–greenstone terranes of the Pilbara Craton, and included what was thought to represent a regionally applicable supracrustal stratigraphy — the Pilbara Supergroup. Recent recognition of separate lithotectonic elements with distinct lithostratigraphy and history has led to the subdivision into five granite–greenstone terranes, including the East and West Pilbara Granite–Greenstone Terranes, separated by the northeast-trending Central Pilbara Tectonic Zone (Fig. 1; Hickman, 2000). It is now recognized that components of the Pilbara Supergroup cannot be correlated across the entire Pilbara Craton (Hickman, 2000; Van Kranendonk et al., 2002). A detailed description of this subdivision and of the geological setting and history of the region is presented by Van Kranendonk et al. (2002).

The geological evolution of the East Pilbara Granite–Greenstone Terrane (EPGGT) on WHITE SPRINGS is

summarized in Table 1. Regionally, the terrane consists of large ovoid granite–gneiss complexes partially surrounded by belts of tightly folded and near-vertically dipping volcanic and sedimentary rocks that are typically metamorphosed to greenschist facies (i.e. greenstones). The oldest dates for greenstones so far are c. 3515 Ma (Table 1; Buick et al., 1995; Van Kranendonk, 1998). Protoliths to the greenstone successions accumulated until c. 2940 Ma, although the majority were deposited before c. 3240 Ma. Felsic magmatism was also active periodically between c. 3600 and c. 2830 Ma. The majority of granites in the eastern part of the terrane intruded before c. 3240 Ma. In contrast, granites dated between c. 2945 and 2930 Ma form a volumetrically significant and locally dominant component of granite complexes in the western part of the terrane, including the Yule Granitoid Complex, on WHITE SPRINGS (Table 1). Champion and Smithies (1998) related these 2945–2930 Ma granites to remelting of older-than-3240 Ma felsic basement.

The boundary between the EPGGT and the Central Pilbara Tectonic Zone is the basal contact between the Mallina Basin and the underlying granite–greenstone sequences. This contact is a fault that may locally be a faulted disconformity. The basement to the Mallina Basin includes chert that has been dated at c. 3015 Ma and is assigned to the Cleaverville Formation of the Gorge Creek Group (Smithies et al., 1999). Deposition of the Cleaverville Formation is the earliest known greenstone-forming event common to both the East and West Pilbara Granite–Greenstone Terranes.

The Mount Bruce Supergroup is a Neoarchaeon to Palaeoproterozoic cover sequence that unconformably overlies the granite–greenstone terranes, and has been described in detail by Hickman (1983), Blake (1993), and Thorne and Trendall (2001). The Fortescue Group forms the lower part of the supergroup and was deposited between c. 2770 and 2630 Ma (Arndt et al., 1991; Nelson, 1997; Wingate, 1999). Blake (1993) suggested that the lower parts of the Mount Bruce Supergroup record a late Archaean period of west-northwesterly–east-southeasterly directed crustal extension, followed by south-southwesterly–north-northeasterly directed rifting of the southern margin of the Pilbara Craton. Conversely, Thorne and Trendall (2001) described the tectonic setting of the Fortescue Group in terms of a single, protracted rifting event.

## Archaean rocks

All rocks of the EPGGT on WHITE SPRINGS have been metamorphosed. Those that retain primary textures are described according to their inferred protolith, and for brevity the prefix ‘meta’ is omitted.

The Archaean geology of WHITE SPRINGS is summarized on the interpreted bedrock geology map figure and the geological history is presented in Table 1. Rocks of the c. 2770–2630 Ma Fortescue Group cover the southwestern part of the map sheet. These rocks are mostly shallowly dipping and only weakly metamorphosed. An unconformity is well developed between the basal unit of the Fortescue Group and the underlying granite–greenstone terrane. The

Table 1. Summary of the geological history of WHITE SPRINGS

| Age (Ma)     | East Pilbara Granite–Greenstone Terrane  |
|--------------|--|
| c. 3420      | Intrusion of protolith to the gneissic rocks of the Yule Granitoid Complex   |
| <3515–>2945  | Deposition of greenstone sequences, and formation of c. 3060 Ma protolith to the Cockeraga Leucogranite  |
| c. 3240      | Amphibolite-facies metamorphism and deformation; 020°–050° trending fabric developed in greenstones of the Western Shaw greenstone belt (TAMBOURAH), and extension of that belt on WHITE SPRINGS |
| <3240–>2945  | Deformation of granitoid–gneiss and greenstone sequences; 110°–160° trending fabric  |
| <3060–2945   | Amphibolite-facies metamorphism, including generation of the Cockeraga Leucogranite from a proximal c. 3060 Ma source region   |
| c. 2945–2930 | Granitic magmatism, including intrusion of the Pincunah, Beabea, Abydos, Woodstock, and Tambourah Monzogranites  |
| c. 2945–2930 | Development of northeast-trending foliation throughout the Yule Granitoid Complex, probably related to northwest–southeast compression of the Central Pilbara Tectonic Zone                      |
| c. 2930–2770 | Erosion  |
| c. 2770      | Deposition of volcanic and sedimentary rocks of the lower Fortescue Group  |
| <2770        | Dip-slip faulting along major northeasterly trending faults  |

lowest two units of the group, the Mount Roe Basalt and Hardey Formation, are not developed on WHITE SPRINGS. Instead, in the northwestern part of the sheet area the Kylene Formation lies at the base of the Fortescue Group, and in the southeast the stratigraphically higher Tumbiana Formation forms the base. This relationship suggests that at the time the Fortescue Group was deposited, the granite–greenstone basement was topographically higher in the southeast than in the northwest. Basalts of the Maddina Formation form the uppermost unit of the Fortescue Group on WHITE SPRINGS.

About 80% of the EPGGT outcrop on WHITE SPRINGS is of granite, all of which belongs to the Yule Granitoid Complex. Gneissic components of this complex form xenoliths within younger granites in the east and northwest of the map sheet. The oldest of the gneissic rocks is the Petroglyph Orthogneiss, which has been dated at c. 3420 Ma (Van Kranendonk, M., 2003, written comm.).

The younger granites are either c. 2930–2945 Ma and typically K-feldspar-porphyritic monzogranites and syenogranites, which dominate to the north and east of the map sheet, or schlieric biotite leucogranite that is 3065 Ma or younger. The former have been described from the adjoining sheets — SATIRIST, WODGINA, and TAMBOURAH — and include the Tambourah, Woodstock, Abydos, and Pincunah Monzogranites. These granites contain xenoliths and roof pendants of greenstone up to 5 km long (e.g. quartzite xenolith at MGA 691000E 7609000N). In the southwestern part of WHITE SPRINGS, a thin, northeast-trending train of roof pendants, including rocks with sedimentary and mafic to ultramafic igneous protoliths, forms the remnants of a faulted synformal greenstone keel, on the northeastern edge of a granitic domal feature (the Tambourah Dome). On WHITE SPRINGS the Tambourah and Woodstock Monzogranites include an unusually large, and locally dominant, amount of pegmatite, which form pods, sheets, and dykes. However, even in areas where pegmatite

is subordinate to monzogranite, preferential weathering of the latter gives a false impression that pegmatite is the dominant component.

Schlieric biotite leucogranites dominate outcrop in the central and northwestern parts of WHITE SPRINGS and have been grouped into the Cockeraga Leucogranite. Like the K-feldspar-porphyritic monzogranites described above, the Cockeraga Leucogranite also contains xenoliths of greenstone and gneiss reaching up to several kilometres in size. However, in the case of the Cockeraga Leucogranite, there are complete gradations between leucogranite, schlieric leucogranite, and greenstone–gneiss successions (xenoliths) that are sheeted or net-veined by leucogranite. The greenstones and gneiss (including xenoliths) have been metamorphosed to at least lower amphibolite facies, and although the greenstones show no evidence of melting, the leucogranite component of the schlieric leucogranite has not migrated far from the source of melting (see below).

Greenstones on WHITE SPRINGS are restricted to xenoliths in, and roof pendants on, granites of the Yule Granitoid Complex. The greenstones cannot be confidently assigned to groups or formations within the Pilbara Supergroup. The thin, northeast-trending train of roof pendants in the southwestern part of WHITE SPRINGS probably forms the extension of the Western Shaw greenstone belt, mapped on TAMBOURAH by Van Kranendonk and Pawley (2002), and is referred to here as the Western Shaw greenstone belt extension (Fig. 3). In the central part of the sheet, abundant greenstone and gneissic xenoliths form the Mount Gratwick xenolith field (Fig. 3).

Amphibolite and metamorphosed ultramafic rock dominate the greenstone outcrops. Subordinate quartzite, metamorphosed chert and banded iron-formation, and biotite-rich schist are either intercalated with amphibolite or form discrete outcrops.



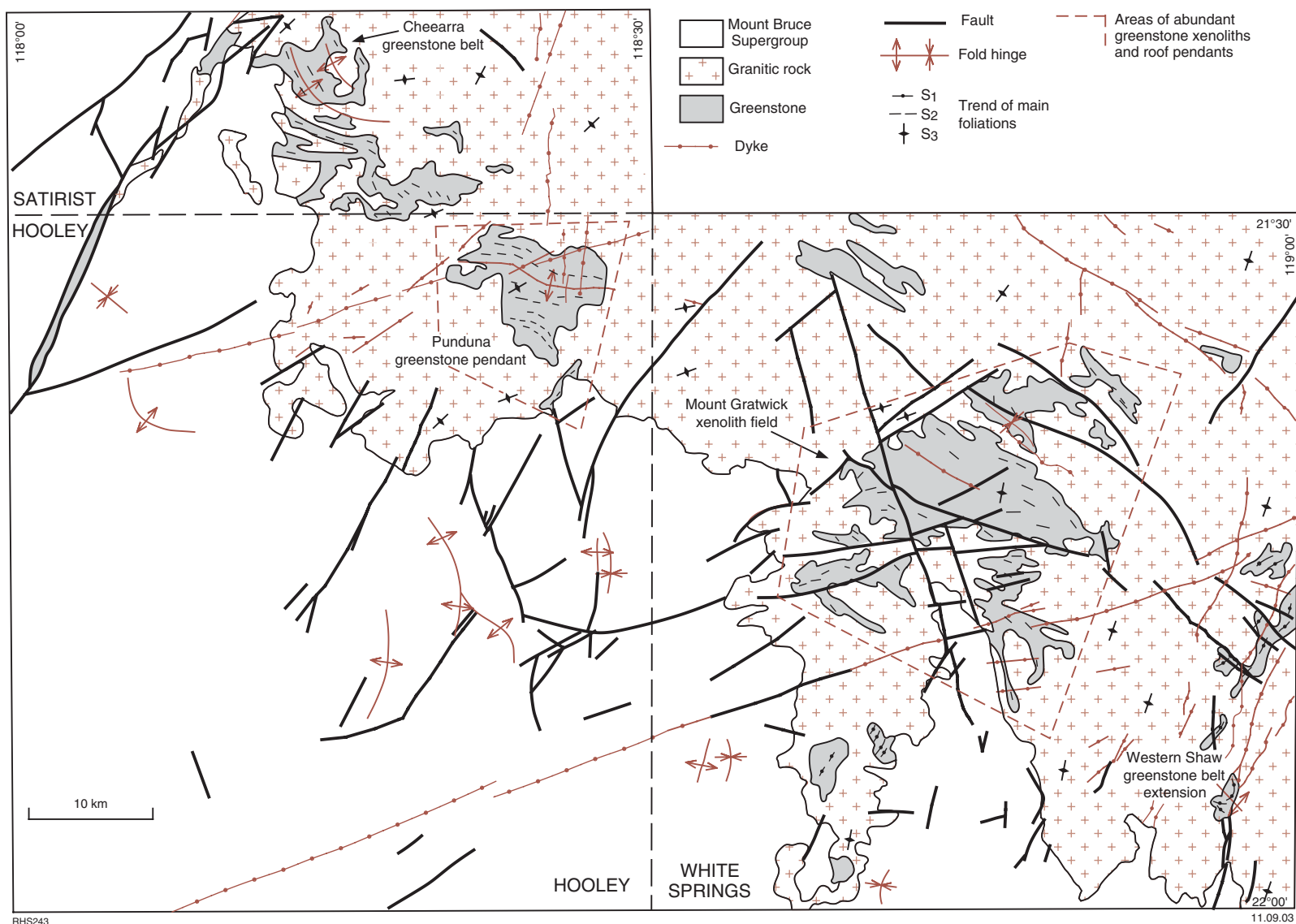


Figure 3. Simplified structural geology of WHITE SPRINGS and some adjacent sheets

## Unassigned greenstone units

### Ultramafic rocks (*Au*, *Aup*, *Aus*, *Aur*)

Outcrops of ultramafic rock that are weathered or strongly deformed have mainly been mapped as undivided ultramafic rock (*Au*). In areas of better exposure, the ultramafic rocks have been subdivided into serpentinitized peridotite (*Aup*), serpentinite and serpentine-rich schist (*Aus*), and tremolite-rich schist (*Aur*).

Undivided ultramafic rock (*Au*), including complexly interleaved combinations of serpentine schist, tremolite schist, and talc–tremolite–chlorite schist, is scattered throughout the sheet area as xenoliths in, or pendants on, the Yule Granitoid Complex. Two large xenoliths are exposed. The first is associated with abundant scattered xenoliths of tremolite-rich schist (*Aur*) in the Cockeraga Leucogranite (*AgYco*; MGA 684000E 7592300N). The second (MGA 703700E 7585000N) forms part of the Western Shaw greenstone belt extension.

Serpentinized peridotite (*Aup*) forms two adjacent xenoliths within the Tambourah Monzogranite (*AgYta*), near the eastern edge of the sheet (MGA 700500E 7573500N). The rock is typically fine to medium grained and massive, with a relic orthocumulate texture. Phenocrysts of olivine, up to 5 mm, and oikocrysts of clinopyroxene, up to 10 mm, are present locally. Olivine is largely to entirely replaced by serpentine and subordinate chlorite, talc, magnetite, tremolite, and carbonate, whereas clinopyroxene is replaced by tremolite, chlorite, talc, and fine-grained magnetite. At some localities (e.g. MGA 700080E 7573439N; MGA 704030E 7586116N) rare and discontinuous layers up to 20 cm thick contain up to 60% chromite. Although serpentinitized peridotite (*Aup*) is restricted in distribution, deformed and schistose derivatives (*Aus*) of this rock are scattered throughout the sheet area as xenoliths in granite.

Tremolite-rich schist (*Aur*) is the most abundant ultramafic rock type, forming locally abundant xenoliths in granites throughout the sheet area. The southern and southeastern exposures of the Cockeraga Leucogranite (*AgYco*) contain abundant xenoliths of tremolite-rich schist, with the largest (MGA 670000E 7569500N) about 2 km in diameter. In the area west and south of White Springs Homestead, extensive outcrops of tremolite-rich schist and undivided ultramafic rock form remnants of what was probably an extensive sheet of ultramafic rock. Tremolite-rich schist is typically fine grained and comprises acicular or fibrous tremolite, with subordinate chlorite, talc, and fine-grained unidentified opaque minerals.

### Mafic rocks (*Aba*, *Abau*, *Abag*, *Abaug*, *Abs*, *Absq*, *Abu*, *Abug*)

The majority of xenoliths in, and roof pendants on, granites of the Yule Granitoid Complex comprise metamorphosed mafic rocks. Two areas where these are particularly abundant are in the Mount Gratwick xenolith field, where they are hosted by the Cockeraga Leucogranite (*AgYco*),

and the Western Shaw greenstone belt extension, which overlies the Tambourah Monzogranite (*AgYta*). At both localities, greenstone is dominated by fine- to medium-grained amphibolite (*Aba*). In the Western Shaw greenstone belt extension, amphibolite is locally interleaved with ultramafic rock (*Abau*) or is extensively intruded by granite dykes and veins (*Abag*), whereas in the Mount Gratwick xenolith field the amphibolite locally contains both interleaves of ultramafic rock and extensive granite intrusions (*Abaug*).

Amphibolite is weakly to strongly foliated and medium grained. It comprises a typically granoblastic assemblage of hornblende, plagioclase, and quartz, and locally also contains clinopyroxene or, less commonly, orthopyroxene. The rocks vary from melanocratic varieties with about 80% hornblende to leucocratic amphibolites with less than 20% hornblende. The amphibolite is typically retrogressed, with variable alteration of hornblende to actinolite and chlorite, and of plagioclase to sericite and epidote. Where metamorphic retrogression is associated with deformation, the rocks are transitional to mafic schist containing actinolite and chlorite (*Abs*).

Strongly sheared mafic schist (*Abs*) is typically a fine- to medium-grained rock containing a variably schistose assemblage of actinolite and chlorite, with minor quartz and plagioclase, and is almost certainly strongly deformed and retrogressed amphibolite. It forms small xenoliths in the Abydos Monzogranite (*AgYab*), in the northeastern part of WHITE SPRINGS (MGA 704200E 7609000N). Xenoliths or roof pendants in the Woodstock Monzogranite (*AgYwo*) locally comprise layers of strongly sheared mafic schist up to 200 m thick, interleaved with quartzite (e.g. MGA 706300E 7601000N). It is unclear if the mafic protolith to the schist was intrusive or extrusive. The Western Shaw greenstone belt extension includes a more extensive unit of strongly sheared mafic schist (*Abs*), which is also locally finely interleaved with quartzite (*Absq*).

Xenoliths of interleaved mafic and ultramafic rocks (*Abu*) are in the Abydos and Woodstock Monzogranites (*AgYab* and *AgYwo*; e.g. MGA 703600E 7609800N). The mafic component is typically a moderately to strongly foliated actinolite–chlorite rock, mineralogically very similar to the strongly sheared mafic schist, with which it is locally associated. The ultramafic component typically comprises tremolite–chlorite schist or serpentinite. Near the contact between the Tambourah and Woodstock Monzogranites (e.g. MGA 704000E 7593000N), interleaved mafic and ultramafic rock is extensively veined and intruded by granite (*Abug*).

### Sedimentary rocks (*Asq*, *Asqn*, *Ac*, *Aci*)

Quartz–muscovite schist and quartzite (*Asq*), after subarkose, forms scattered xenoliths in the Woodstock Monzogranite (*AgYwo*) on the eastern edge of WHITE SPRINGS (e.g. MGA 706400E 7601600N), and an approximately 4 km-long, northwest-trending, xenolith within gneissic granodiorite in the area between Logan Well and the Great Northern Highway in the northeast. Quartz–muscovite schist and quartzite contain between 70 and

95% quartz. The rocks with less quartz are locally well banded. The bands are defined by feldspar-rich layers or a prominent schistosity produced by alignment of muscovite, or a combination of both. The more quartz-rich rocks are typically massive and comprise a granoblastic assemblage of quartz–plagioclase (now epidote and sericite) and rare microcline and clinopyroxene, with actinolite as a late-crystallizing acicular mineral. The amount of amphibole increases locally in 10 cm- to 1 m-scale bands, forming a distinct unit (quartzite with local banded quartz and quartz–feldspar–amphibole paragneiss — *Asqn*). This banding almost certainly reflects original sedimentary layering.

Rare xenoliths of white chert, and locally banded white and grey chert (*Ac*) in the western end of the Western Shaw greenstone belt extension (MGA 699600E 7578700N; MGA 700800E 7573200N; MGA 701500E 7575200N) are locally associated with banded iron-formation (*Aci*; MGA 699300E 7578700N). Centimetre-scale banding in the banded white and grey chert is defined by alternating assemblages of coarse-grained granoblastic quartz and fine- to medium-grained quartz, feldspar and iron-oxides, and possibly reflects primary banding within a clastic protolith.

## Yule Granitoid Complex

Van Kranendonk (2003) described the Yule Granitoid Complex on TAMBOURAH as composed of two structural domains: the main part of the complex in the west, and the Tambourah Dome in the east. Both components are also on WHITE SPRINGS, with the Tambourah Dome in the southeastern corner of the sheet area. The two domains are separated by a strongly deformed, synformal roof pendant of greenstones that becomes progressively more digested by granite to the southwest and onto WHITE SPRINGS (Hickman, 1983), and is referred to here as the Western Shaw greenstone belt extension. In the central and northern parts of WHITE SPRINGS, the Yule Granitoid Complex includes rocks too strongly weathered (*AgY*) to be confidently assigned to any particular unit (e.g. MGA 678700E 7615300N). Similar weathered granite (labelled *Ag*) forms dykes in tremolite–chlorite schist (*Aur*) in the southeastern part of WHITE SPRINGS.

## Older components of the Yule Granitoid Complex

### Unassigned gneiss (*AgYn*, *AgYnl*)

Xenoliths of felsic gneiss are locally common within the K-feldspar–porphyritic monzogranites and the schlieric biotite leucogranite on WHITE SPRINGS, but only rarely do these form discrete mappable bodies (e.g. MGA 689200E 6700700N and 692500E 7595000N). Such bodies are of equigranular to feldspar–porphyritic biotite orthogneiss (*AgYn*), and are locally intruded by abundant medium- to coarse-grained leucogranite and pegmatite (to form the unit *AgYnl*). Although these gneissic units outcrop close to greenstone, they contain no greenstone xenoliths and are, on that basis, interpreted to pre-date the greenstones.

### Petroglyph Orthogneiss (*AgYpt*, *AgYptx*)

The Petroglyph Orthogneiss (*AgYpt*), locally with abundant greenstone and granitic gneiss xenoliths (*AgYptx*), forms the oldest known mappable component of the Yule Granitoid Complex. According to Van Kranendonk (2003), these rocks are preserved as remnants in younger granites along the outer margin of the Tambourah Dome, and as scattered inclusions within the main complex. A sample dated from TAMBOURAH gave a U–Pb sensitive high-resolution ion microprobe (SHRIMP) age of c. 3420 Ma (Van Kranendonk, M., 2003, written comm.). On WHITE SPRINGS the Petroglyph Orthogneiss outcrops in the Western Shaw greenstone belt extension, where it represents locally preserved basement to greenstones. Van Kranendonk (2003) described the orthogneiss unit as comprising blue-grey biotite granite, with sheeted leucogranite veins, and a more mesocratic biotite–hornblende-bearing and plagioclase–porphyritic quartz diorite to quartz monzodiorite.

## Younger components of the Yule Granitoid Complex

### Cheearra Monzogranite (*AgYchm*, *AgYchn*)

Equigranular to porphyritic biotite monzogranite (*AgYchm*) forms a small outcrop in the far north of WHITE SPRINGS (MGA 667000E 7621600N). A weak to locally strong foliation is defined by the alignment of biotite and chlorite and flattened quartz grains, or by zones of granoblastic quartz, micaceous schlieren, and K-feldspar phenocrysts. Biotite is the only mafic silicate mineral and typically constitutes less than 8% of the rock. Quartz (typically granoblastic), perthite, and biotite form interstitially to plagioclase, but are all locally included within large (up to 2 cm in length), late-crystallizing grains of microcline. Accessory minerals include apatite, zircon, rutile, titanite, allanite, and magnetite (now leucoxene).

Monzogranitic to granodioritic gneiss (*AgYchn*) forms small outcrops in the far northern and western parts of WHITE SPRINGS (MGA 662000E 7617300N), and locally forms xenoliths within later schlieric leucogranites (*AgYco*). The unit includes hornblende-rich granodioritic and tonalitic varieties, and is mineralogically identical to, and texturally transitional from, moderately to strongly foliated monzogranite (*AgYchm*). Mesocratic and leucocratic bands are locally well developed and some stromatic outcrops contain banding. Leucogranitic and pegmatitic patches, commonly with mafic selvages, also appear to have accumulated in fractures or in hinge zones of minor folds. This suggests local, incipient, partial melting of the gneissic granitic rock.

### Cockeraga Leucogranite (*AgYco*, *AgYcor*, *AgYcope*)

The Cockeraga Leucogranite is the most widespread unit on WHITE SPRINGS and dominates outcrop in the western half of the sheet area. The unit comprises leucocratic biotite(–hornblende) tonalite or granodiorite, with rare monzogranite (*AgYco*), and commonly shows a distinctive, well-developed, schlieric banding (*AgYcor*). The unit is also locally intruded by abundant pegmatite (*AgYcope*).



The unit ranges from medium to coarse grained and is highly variable at outcrop scale, comprising an accumulation of individual sheets and veins, readily identified by abrupt changes in grain size and mineralogy. Inclusions range in size from single grains up to kilometre-scale blocks, and include metasedimentary, granitic, and mafic to ultramafic igneous protoliths. Schlieren typically represent variably disaggregated xenolithic material, which is in some cases demonstrably of local origin. In thicker leucogranite units, schlieren are typically strongly attenuated, but become more common and more angular towards contacts with greenstone country-rock or xenoliths. The greenstone country-rock or xenoliths are metamorphosed at least to lower amphibolite facies, and become increasingly invaded (net-veined) or swamped, and disaggregated by leucogranite near leucogranite sheets. Biotite is the predominant mafic mineral in the schlieren, but is accompanied by hornblende where the leucogranite has intruded mafic xenoliths. A flow foliation is particularly well defined in the schlieren-rich rocks, with irregular 'swirls' that do not conform to regional structural trends, and locally wrap around xenoliths (Fig. 4).

The age of the leucogranite has not been clearly determined. The youngest population of zircons from two samples (GSWA 169014 and 169016, MGA 675720E 7595740N) provided an age (U–Pb SHRIMP) of c. 3065 Ma (Nelson, 2002). While this may be the crystallization age of the rocks, geochemical data (Geological Survey of Western Australia – Geoscience Australia, unpublished data) suggest that these rocks are the result of disequilibrium melting, and still contain abundant restite. The interpretation preferred here is that the age obtained (c. 3065 Ma) represents the minimum age of the source and the maximum age of the leucogranite.

### ***Pincunah Monzogranite (AgYpi)***

The Pincunah Monzogranite (*AgYpi*) comprises moderately to strongly feldspar(–quartz)–porphyritic biotite (–hornblende) monzogranite, and outcrops in the northeast, around White Well. The rock is weakly to moderately foliated and typically shows a strong flow alignment of tabular K-feldspar phenocrysts, which are up to 2 cm in length. Quartz phenocrysts are typically subhedral to anhedral and less than 6 mm in diameter.

### ***Beabea Monzogranite (AgYbe)***

The Beabea Monzogranite (*AgYbe*) comprises equigranular to, more typically, feldspar-porphyritic monzogranite and rare granodiorite. These rocks outcrop in the southwestern part of WHITE SPRINGS, where they have been locally intruded by, and included within, the Tambourah Monzogranite (*AgYta*; e.g. MGA 702000E 7586400N). The rock is typically weakly foliated. Tabular phenocrysts of K-feldspar, up to 3 cm in length, are typically randomly oriented, but locally show an alignment that is interpreted here as a flow alignment. Subhedral grains of zoned plagioclase, up to 5 mm in size, are locally present in rocks transitional to granodiorite. SHRIMP

U–Pb dating of zircons from a sample of K-feldspar-porphyritic monzogranite (GSWA 169018; MGA 694890E 7585210N) gave an age of  $2941 \pm 4$  Ma, which is interpreted to be the age of igneous crystallization (Nelson, 2002).

### ***Abydos Monzogranite (AgYab, AgYabn, AgYabx)***

The Abydos Monzogranite (*AgYab*) outcrops in the northeastern part of the sheet, between outcrops of the Pincunah Monzogranite (*AgYpi*) and Woodstock Monzogranites (*AgYwo*). It is a moderately to strongly foliated, K-feldspar- and quartz-porphyritic and titanite-bearing biotite monzogranite to syenogranite. It locally includes abundant xenoliths of granitic gneiss (*AgYabn*) and greenstone (*AgYabx*). K-feldspar forms subhedral to euhedral phenocrysts up to 2.5 cm in length, whereas anhedral quartz phenocrysts are typically less than 5 mm across. Subhedral to euhedral prisms of titanite reach 4 mm in length, and are a distinctive feature of the rock. Ghost banding is locally well developed, forming northerly trending zones up to a kilometre wide.

### ***Woodstock Monzogranite (AgYwo, AgYwox)***

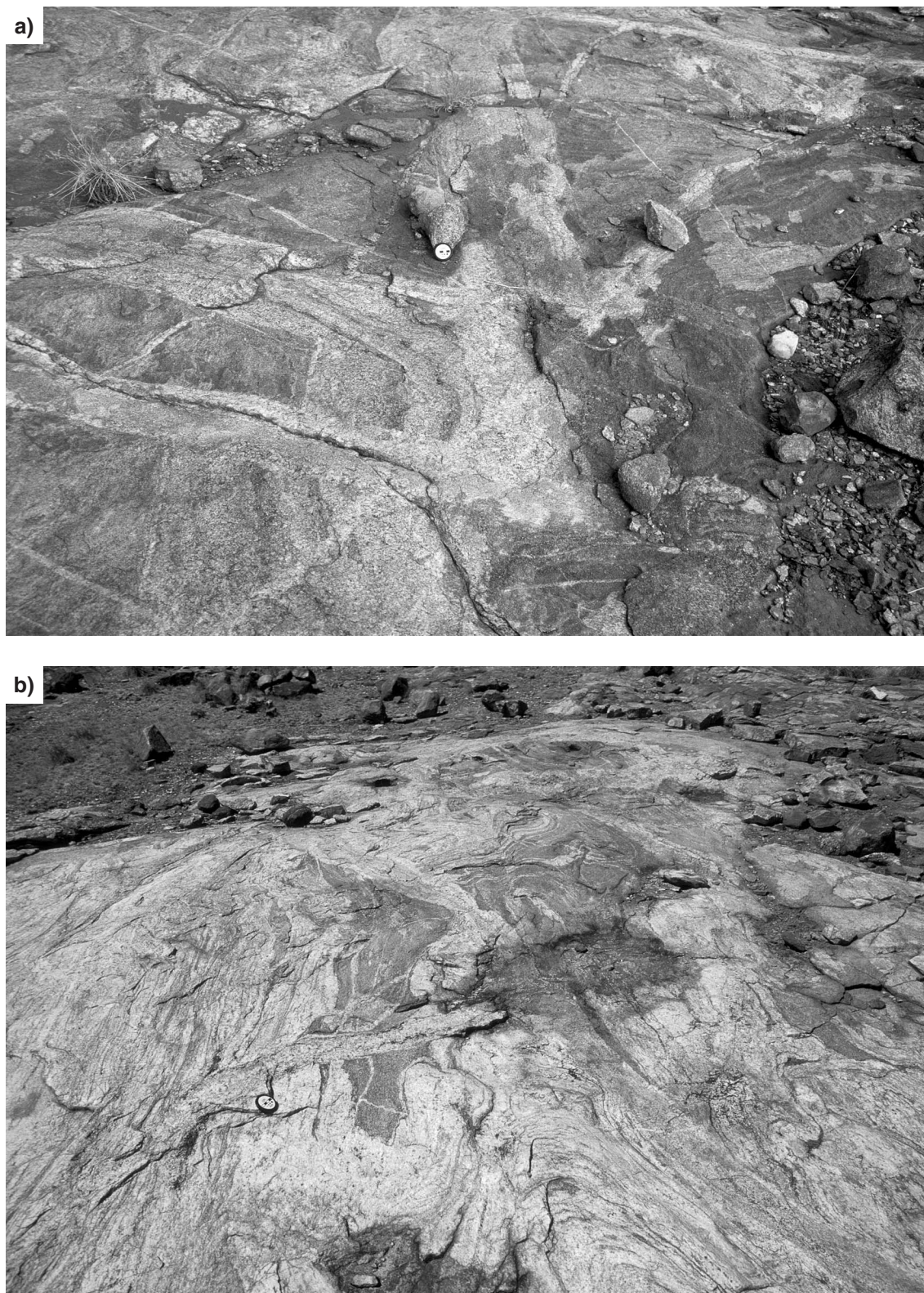
The Woodstock Monzogranite (*AgYwo*), locally with abundant xenoliths of greenstone and gneiss (*AgYwox*), outcrops in the northeastern part of the sheet, south of the Abydos Monzogranite (*AgYab*). It is typically an equigranular to feldspar-porphyritic biotite monzogranite, with microcline forming tabular phenocrysts up to 1.5 cm in size. These phenocrysts are a late-crystallizing phase that grow around all earlier crystallizing phases including biotite. These rocks are typically richer in microcline (both phenocrystic and interstitial) than the Beabea Monzogranite (*AgYbe*), but contain less microcline than the Abydos Monzogranite (*AgYab*). The Woodstock Monzogranite is typically also coarser grained than the latter two rock types.

The Woodstock Monzogranite on TAMBOURAH has been described in detail by Van Kranendonk (2003), and has been dated at  $2933 \pm 3$  Ma (Nelson, 1998). On TAMBOURAH this unit is well foliated and locally mylonitized within shear zones.

### ***Tambourah Monzogranite (AgYta, AgYtax, AgYtan)***

The Tambourah Monzogranite (*AgYta*) is a very heterogeneous unit dominated by coarse-grained biotite syenogranite, but locally also containing abundant, very coarse grained syenogranite and pegmatite. The syenogranite typically contains more biotite (around 10%) than rocks of the Beabea, Abydos, and Woodstock Monzogranites (*AgYbe*, *AgYwo*, *AgYab*). Weathering locally results in preferential degradation of the syenogranite, and so the actual abundance of pegmatite in the Tambourah Monzogranite is easily overestimated. Nevertheless, pegmatite locally accounts for up to 20% of the outcrop, forming discrete dykes and sheets, and more diffuse irregular patches. North of the Western Shaw greenstone belt extension, the Tambourah Monzogranite





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**Figure 4.** The Cockeraga Leucogranite, showing typical examples of strongly banded schlieric leucogranite (light material) swamping or invading (a), and eventually enclosing as xenolith (b) gneissic granite. Lens cap is 4 cm across



contains abundant xenoliths of greenstones and gneiss and was mapped separately (*AgYtax*). In the far southeast of WHITE SPRINGS, coarse-grained syenogranite and pegmatite form abundant irregular sheets within medium- to coarse-grained biotite–hornblende granodioritic gneiss (*AgYtan*).

**Other younger components of the Yule Granitoid Complex, including pegmatite (*AgYipe*, *AgYipex*, *AgYt*, *AgYl*, *AgYln*, *AgYlpe*, *AgYlnpe*, *AgYlpex*, *AgYpe*, *AgYpex*)**

Interleaved banded and gneissic granodiorite, seriate to porphyritic monzogranite, and pegmatite (*AgYipe*), locally with abundant greenstone xenoliths (*AgYipex*), outcrops along the northern margin of WHITE SPRINGS. These units are complexly interleaved or intermixed. However, to the north (on WODGINA) the monzogranite locally grades into the less foliated Cheearra Monzogranite, which, although undated, is geochemically indistinguishable from local c. 2930–2945 Ma monzogranites described by Champion and Smithies (2000).

Coarse-grained and massive hornblende–biotite tonalite (*AgYt*) outcrops about 9 km west of White Springs Homestead (at MGA 677686E 7592210N) where it is unconformably overlain by rocks of the Fortescue Group. This tonalite is highly leucocratic and is mineralogically identical to the schlieren-free tonalitic component of the Cockeraga Leucogranite (*AgYco*), of which it is possibly an unfoliated correlative.

In the central part of WHITE SPRINGS, straddling the Great Northern Highway, there are widespread but scattered outcrops of medium-grained leucogranite (*AgYl*), dominated by monzogranite and syenogranite, but also including lesser amounts of granodiorite and tonalite. The leucogranite locally includes abundant xenoliths of gneiss (*AgYln*), or is intruded by abundant sheets, veins, and bodies of pegmatite (*AgYlpe*), or includes both pegmatite and xenoliths of granitic gneiss (*AgYlnpe*) and greenstone (*AgYlpex*). The leucogranites vary widely in mineralogy and texture. Syenogranites, monzogranites, and granodiorites are locally K-feldspar porphyritic, whereas the mafic mineralogy of the monzogranites, granodiorites and tonalites may include either or both biotite and hornblende. These rocks outcrop between the Cockeraga Monzogranite (*AgYco*) and the region that comprises the Tambourah, Beabea, Woodstock, and Pincunah Monzogranites (*AgYta*, *AgYbe*, *AgYwo*, *AgYpi*). All of these lithologies are at least locally highly leucocratic, and may be similar in age. The medium-grained leucogranite (*AgYl*) unit may contain components from some or all of these rock types.

Pegmatite (*AgYpe*), locally containing abundant xenoliths of greenstone and gneiss (*AgYpex*), forms very scattered outcrops in the central part of WHITE SPRINGS, where it is closely associated with medium-grained leucogranite (*AgYl*). The pegmatite has typically intruded as a series of dykes and sheets and more-diffuse irregular patches, rather than as larger coherent stocks or layers.

## Metamorphism and structure of the East Pilbara Granite–Greenstone Terrane on WHITE SPRINGS

### Metamorphism

Throughout the EPGGT, metamorphism that occurred before deposition of the Fortescue Group appears to relate primarily to repeated granite intrusion. Most rocks of the EPGGT are metamorphosed to low- to middle-greenschist facies, characterized by chlorite–actinolite–albite(–epidote) in mafic rocks and albite–biotite(–white mica – chlorite) in pelitic rocks. Amphibolite-facies assemblages are in places developed close to contacts with granites, and particularly to larger bodies of tonalitic to granodioritic composition. For example, to the northwest of WHITE SPRINGS, mafic rocks of the Pilbara Well greenstone belt preserve an upper amphibolite-facies assemblage of calcic-plagioclase–hornblende (–clinopyroxene) adjacent to the Yule Granitoid Complex (Smithies and Farrell, 2000).

Smithies and Farrell (2000) noted that on SATIRIST the Cheearra Monzogranite (*AgYch*) of the Yule Granitoid Complex shows a progressive southerly increase in metamorphic grade. It is not clear if this metamorphic trend is related to local intrusion of granitic rocks or is more regional in nature, reflecting a southerly increase in structural depth. Stromatic banding is a feature of some outcrops near the southern boundary of SATIRIST, and pegmatitic patches, commonly with mafic selvages, appear to have accumulated in fractures or in hinge zones of minor folds, suggesting local, incipient partial melting of the gneissic granitic rock. The Mungaroona Granodiorite (on SATIRIST), which intruded both the gneissic granitic rocks and greenstones at c. 2945 Ma (Nelson, 2000), provides a minimum age for this metamorphism.

All greenstones (in xenoliths and roof pendants) on WHITE SPRINGS have been metamorphosed to at least lower amphibolite facies. Although the mineralogy of most rocks reflects extensive retrogression, preservation of the peak metamorphic assemblage — hornblende–plagioclase (–clinopyroxene) — is widespread. This supports the observation that the metamorphic grade increases from north to south in the western part of the EPGGT (Smithies and Farrell, 2000), but does not clarify the nature of metamorphism (i.e. contact or regional metamorphism). On the one hand, all rocks of the Pilbara Supergroup on WHITE SPRINGS are within 1 km or less of younger granites, and on the other hand, although there is no evidence for in situ melting of either greenstone or gneiss xenoliths or country rock, unpublished geochemical data suggest that the Cockeraga Leucogranite (*AgYco*) is a disequilibrium melt representing a very low degree partial melt that was rapidly extracted from a proximal source. The rocks of the Cockeraga Leucogranite have invaded, disaggregated, and included greenstones on all scales. Greenstone and gneiss are locally swamped, or net-veined, and some outcrops containing a large proportion of leucogranite are best described as injection migmatite.

The available geochronology (Nelson, 2002) suggests that melting of source rocks to produce the Cockeraga Leucogranite occurred at or before c. 3065 Ma. Peak metamorphic temperatures in the northwestern part of the EPGGT (e.g. on SATRIST) and in the Mallina Basin region occurred at c. 2950 Ma (Smithies and Farrell, 2000). However, structures defined by amphibolite-facies assemblages of the Western Shaw greenstone belt on TAMBOURAH can be related to a c. 3240 Ma phase of deformation (Van Kranendonk, 2003). Hence, the metamorphic history of the WHITE SPRINGS region may be long and complex.

## Structure

The Yule Granitoid Complex on WHITE SPRINGS comprises numerous generations of granitic rocks, with ages between c. 3420 and 2930 Ma. All phases contain a weak east-northeasterly foliation (shown as  $S_3$  in Fig. 3). Except for foliations developed adjacent to late faults, this foliation is the only deformational fabric developed in the younger (c. 2945 to 2930 Ma) granites of the complex. Some of these younger granites, such as the Pincunah Monzogranite (*AgYpi*), locally show an alignment of K-feldspar phenocrysts parallel to this late foliation direction, possibly reflecting late-tectonic intrusion.

In the gneissic granites and greenstones that form xenoliths and roof pendants, the late east-northeasterly trending foliation overprints gneissic banding or strongly developed foliation. In many cases this earlier fabric is randomly oriented due to rotation of the xenoliths. Where this has not happened, the fabric typically dips steeply. In the northwestern part of WHITE SPRINGS this fabric strikes between about 110° and 160° ( $S_2$  on Fig. 3), whereas in the southeastern part the strike typically varies between 020° and 050° ( $S_1$  on Fig. 3). In the central part of the sheet, between Outcamp Well and Tabletop Well, the  $S_2$  fabric overprints the  $S_1$  fabric. In the Western Shaw greenstone belt extension, the early 020°–050° fabric trends parallel to lithological contacts and is folded about northwest-trending fold axes (MGA 701700E 7575200N; MGA 700600E 7573500N). Van Kranendonk (2003) suggested that foliations and lineations defined by amphibolite-facies mineral assemblages in the Western Shaw greenstone belt (the continuation, on TAMBOURAH, of the Western Shaw greenstone belt extension) relate to a c. 3240 Ma phase of deformation. If this is the case, the later  $S_2$  fabric is constrained to between c. 3240 and 2945 Ma.

In the area of the Yule Granitoid Complex that includes the Mount Gratwick xenolith field, there appears to be a broad correspondence between xenolith-rich areas and broad, poorly defined, northwest-trending synclinal structures, and between areas with fewer xenoliths and broad, poorly defined anticlinal structures (see cross section on map). This relationship possibly suggests migration of the Cockeraga Leucogranite into earlier formed anticlinal structures.

## Fortescue Group

The Fortescue Group is a c. 2770–2630 Ma succession of dominantly basaltic rocks that extends across much of the

Pilbara Craton, and outcrops almost continuously in the southwestern corner of WHITE SPRINGS. The contact with the granite–greenstone terrane is an angular unconformity. Polymictic conglomerate containing subrounded clasts derived from the underlying granite–greenstone terrane, and medium- to coarse-grained, poorly sorted sandstone locally mark the base of the group on WHITE SPRINGS, but are commonly too thin and irregular to be represented at 1:100 000 scale. The rocks typically dip shallowly to the southwest with a resultant gradual southerly progression to higher stratigraphic levels. The regional stratigraphy of the group has been reviewed by Hickman (1983) and Thorne and Trendall (2001).

## Unassigned units (*AF(st)*)

Although typically too thin to represent at map scale, thicker mappable units of medium- to coarse-grained, poorly sorted sandstone (*AF(st)*) mark the basal unconformity of the Fortescue Group in the area around Cooletha Hill. This feldspathic sandstone appears to have been primarily derived from eroded granite, but a locally high abundance of chlorite and pebbles of various types (e.g. chert, metabasalt, metasandstone) probably reflects some contribution from eroded greenstones.

## Kylena Formation (*AFk*, *AFkbi*)

The Kylena Formation (*AFk*), previously the Kylena Basalt but renamed and redefined by Kojan and Hickman (1998), conformably or disconformably overlies the Hardey Formation on SATRIST, but forms the basal unit of the Fortescue Group in the southwestern part of WHITE SPRINGS. The unit typically comprises flows of massive to amygdaloidal basalt and basaltic andesite, and is known regionally to also contain minor layers of high-Mg basalt, dacite, and rhyolite (Kojan and Hickman, 1998). Layers in which basaltic andesite appear to dominate were mapped separately (*AFkbi*). Alteration of basalt to an assemblage containing quartz, sericite, and pyrophyllite is locally intense, particularly within beds of mafic volcanoclastic (breccia) rocks. This alteration produces bleached zones that are readily identifiable on aerial photography (e.g. MGA 685103E 7576894N and MGA 657057E 7600062N) and is interpreted to represent syn- to late-volcanic epithermal-style alteration.

## Tumbiana Formation (*Aftsv*, *Aftslv*, *Aftb*, *Aftc*)

The Tumbiana Formation conformably overlies the Kylena Formation in the southwestern part of WHITE SPRINGS, but in the southeast it directly overlies either granitoid basement or unassigned poorly sorted sandstone (*AF(st)*). Four subdivisions of this formation are recognized on WHITE SPRINGS, the dominant and typically basal component being volcanoclastic sandstone with minor tuff and carbonate rock (*Aftsv*). Volcanoclastic siltstone and tuff (*Aftslv*), locally with abundant layers of medium-grained volcanoclastic sandstone, forms a minor component that does not appear to be restricted to a specific stratigraphic level. Massive and variably vesicular basalt (*Aftb*) locally



forms a component that is up to about 40 m thick. Where the basalt is present, it typically underlies the Meentheena Member (*AFtc*), which comprises dark-grey stromatolitic dolomite and limestone as well as subordinate carbonate-rich tuff, mudstone, and siltstone, which Thorne and Trendall (2001) interpreted to have accumulated in a low-energy shallow coastal setting.

### Maddina Formation (*AFm*, *AFmk*)

The Maddina Formation forms the stratigraphically highest unit of the Fortescue Group on WHITE SPRINGS. It typically consists of massive, vesicular, and amygdaloidal basalt and basaltic andesite (*AFm*), but also includes a distinct layer of mafic volcanoclastic sandstone, mudstone, chert, and dolomite (the Kuruna Member, *AFmk*), which Thorne and Trendall (2001) interpreted to have accumulated in a low-energy shallow coastal setting.

### Dolerite dykes (*AF(d)*)

The north-northeasterly trending dolerite dykes in the East Pilbara Granite–Greenstone Terrane are considered to be co-magmatic with mafic units of the Fortescue Group (Van Kranendonk, 2003). These dykes are common on the eastern edge of WHITE SPRINGS. To the east, on TAMBOURAH, the north-northeasterly trending Black Range Dolerite Dyke has been dated at  $2772 \pm 2$  Ma (Wingate, 1999), which is a similar age to the basal Mount Roe Basalt of the Fortescue Group (Arndt et al., 1991). Van Kranendonk (2003) pointed out that although many north-northeasterly trending dolerite dykes might also be of this age, a  $2747 \pm 4$  Ma age corresponding to the eruption of the Kylenea Formation was obtained by Wingate (1999) from the southeastern part of the Pilbara Craton.

### Structure and metamorphism of the Fortescue Group on WHITE SPRINGS

On WHITE SPRINGS, bedding surfaces within the Fortescue Group typically dip at a shallow angle, predominantly to the south-southwest. The southwestern part of WHITE SPRINGS has broad northerly trending folds.

Northeasterly trending faults are a common and significant feature throughout WHITE SPRINGS. The faults contain evidence of both strike-slip and dip-slip displacements. However, the latter appears to have occurred after deposition of the Fortescue Group. North-northwesterly trending faults show a dip-slip component that has locally (MGA 666000E 7599600N) juxtaposed Fortescue Sandstone (*AF(st)*) against the Kylenea Formation. These faults have also focused epithermal fluids that produced sericite–pyrophyllite alteration assemblages similar to those in bedding-parallel zones within the Kylenea Formation. The alteration minerals have filled open spaces created during synchronous fault movement. This alteration is interpreted here to be synvolcanic with respect to either or both the overlying Maddina Formation or the Kylenea Formation itself. Hence, the north-northwesterly trending faults are likewise interpreted to be syn-Fortescue Group in age.

The rocks of the Fortescue Group have been subjected to low-grade metamorphism, characterized in the mafic rocks by an assemblage containing chlorite and epidote.

### Quartz–feldspar porphyry dyke (*Apf*), dolerite dykes (*d*, *dx*), and quartz veins (*q*)

A northwest-trending quartz–feldspar porphyry dyke (*Apf*), up to 10 m wide, intrudes the Cockeraga Leucogranite (*AgYco*) immediately south of White Springs Homestead. The dyke is intruded by east-northeasterly trending dolerite dykes (*d*) and is assumed to be Archaean in age. The rock is fine to medium grained, with phenocrysts of subhedral to euhedral plagioclase, anhedral and embayed quartz, and subhedral biotite, each up to 2 mm, in a groundmass dominated by granular plagioclase and intergranular quartz.

Dolerite dykes (*d*) of undetermined age are common throughout WHITE SPRINGS, particularly on the eastern edge of the sheet area. They typically trend either east-northeast or northwest. Some east-northeasterly trending dykes are locally extensively altered and crowded with subrounded and partially resorbed granite and quartz (?vein) xenoliths (*dx*). In these dykes, chlorite and epidote have replaced all primary mafic minerals and plagioclase is extensively sericitized.

Quartz veins (*q*) outcrop along, and are parallel to, mostly late northwesterly trending faults. At some localities (e.g. MGA 673700E 7595700N), the veins show colliform and bladed textures typical of epithermal quartz veins.

## Cainozoic deposits

### Residual deposits (*Czru*, *Czrk*, *Czrg*, *Czrf*)

Massive, grey siliceous caprock over ultramafic rock (*Czru*) is associated with altered outcrop of unassigned ultramafic rocks, mainly in the northern (MGA 687000E 6715500N) and central (MGA 686000E 7586000N) parts of the sheet area.

Massive, nodular, and cavernous calcrete of residual origin (*Czrk*) is present throughout WHITE SPRINGS, particularly in the southern and central parts of the sheet area. It is most commonly developed over mafic and ultramafic rocks (MGA 673000E 7619500N), where it is locally associated with minor deposits of magnesite.

Relict colluvial sand, gravel, and silt overlying and derived from granitoid (*Czrg*) occupies large areas in the northern half of the sheet area, typically forming slightly elevated, but highly dissected, areas surrounded by younger, coarse-grained colluvial deposits.

Ferricrete (*Czrf*) or ferruginous duricrust, including ferruginous and pisolitic ironstone, is exposed in the

central parts of WHITE SPRINGS (MGA 677000E 7590500N) in areas around basaltic rocks of the Fortescue Group. The unit forms laterite platforms that are slightly elevated compared to adjacent colluvial deposits.

## Colluvium (*Czc, Czcf, Czcg, Czcb*)

Dissected and consolidated colluvium (*Czc*) is exposed in outwash fans flanking elevated exposures of the Fortescue Group in the southern and western parts of WHITE SPRINGS. These deposits consist of clay- or silica-cemented, poorly stratified silt, sand, and gravel, and locally (e.g. MGA 670000E 7575000N) contain abundant ferruginous silt, sand, and gravel bound by a limonitic cement (*Czcf*). In the central and eastern parts of the sheet, extensive areas of quartzofeldspathic colluvium have been derived from granite (*Czcg*), which forms an elevated region along the far eastern side of the sheet. In the far southwest of the sheet area, a gilgai surface has developed over colluvial deposits (*Czcb*). Gilgai is a clay-rich silt or sand deposit characterized by the development of numerous cracks and sinkholes. The clay expands and contracts according to water content, and in dry conditions produces an irregular 'crabhole' surface.

## Alluvial deposits (*Cza, Czag, Czak*)

High-level alluvial deposits, dissected by recent drainage, are exposed throughout WHITE SPRINGS and are most common in the northern parts of the sheet where they extensively overlie granites. These typically clay cemented, poorly stratified deposits consist either of sand, silt, and gravel layers (*Cza*) or are primarily gravel (*Czag*). Massive, nodular, and cavernous calcrete of alluvial origin (*Czak*) has formed along old drainage channels (MGA 657300E 7621300N).

## Quaternary colluvium, outwash-fan deposits, and quartzofeldspathic eluvial sand (*Qc, Qwg, Qrg*)

Colluvium, consisting of sand, silt, and gravel (*Qc*) is locally derived from elevated outcrops and deposited as sheetwash and talus. Sheetwash, including sand, silt, and clay, is deposited on distal outwash fans, and in some regions (e.g. MGA 684000E 7590000N) it overlies, and is derived from granite (*Qwg*). Locally reworked by wind action, the sand deposits are commonly stabilized by extensive grass and shrub cover.

Quartzofeldspathic eluvial sand with quartz and rock fragments (*Qrg*) overlies, and has been derived from, a large proportion of granites of the Yule Granitoid Complex.

## Quaternary alluvial deposits (*Qaa, Qao, Qab, Qaoc*)

Present-day drainage channels contain alluvial clay, silt, and sand in channels on floodplains, and sand and gravel in rivers and creeks (*Qaa*). Alluvial clay, silt, and sand form overbank deposits on floodplains (*Qao*) and locally include gilgai (*Qab*). In areas immediately adjacent to rivers, alluvial floodplains also include small, abundant, scattered lacustrine or claypan deposits (*Qaoc*), consisting of clay, silt, and evaporite in shallow depressions.

## Economic geology

A detailed description of the mineral occurrences and exploration potential of the East Pilbara Granite–Greenstone Terrane was provided by Ferguson and Ruddock (2001), from which the following summary is drawn. There are no known gold localities and few other commodity locations on WHITE SPRINGS.

Alluvial tin, with or without tantalum, has been mined from the Pinga Creek area (between MGA 685920E 7621210N and MGA 688200E 7619710N) in the northern part of the sheet. According to Blockley (1980), a total of 37.15 tonnes of tin concentrate was produced from the Pinga Creek area.

A narrow hydrothermal quartz vein (MGA 698562E 7610362N) in the Woodstock Monzogranite, about 4.3 km northwest of Woodstock Homestead, contains base metal (zinc and copper) mineralization that has been exploited over a strike length of 30 m (Blockley, 1971). There are minor chrysotile asbestos deposits at White Ridge (MGA 691987E 7582606N) in an ultramafic xenolith within medium- to coarse-grained leucogranite (*Agylpe*).

Apart from these documented mineral occurrences, serpentinitized peridotite containing up to 60% chromite was noted at two localities (MGA 700080E 7573439N and MGA 704030E 7586116N) during the course of mapping WHITE SPRINGS. The chromite forms rare and discontinuous layers up to 20 cm thick within tectonically dismembered peridotite bodies.

## References

- ARNDT, N. T., NELSON, D. R., COMPSTON, W., TRENDALL, A. F., and THORNE, A. M., 1991, The age of the Fortescue Group, Hamersley Basin, Western Australia, from ion microprobe zircon U–Pb results: *Australian Journal of Earth Sciences*, v. 38, p. 261–281.
- BARLEY, M. E., 1997, The Pilbara Craton, in *Greenstone belts edited by M. J. DE WIT and L. D. ASHWALL*: Oxford University Press, p. 657–664.
- BEARD, J. S., 1975, The vegetation of the Pilbara area: University of Western Australia Press, 1:100 000 Vegetation Series Map and Explanatory Notes, 120p.
- BLAKE, T. S., 1993, Late Archaean crustal extension, sedimentary basin formation, flood basalt volcanism, and continental rifting: the Nullagine and Mount Jope supersequences, Western Australia: *Precambrian Research*, v. 60, p. 185–242.
- BLOCKLEY, J. G., 1971, The lead, zinc and silver deposits of Western Australia: Western Australia Geological Survey, Mineral Resources Bulletin 9, 234p.
- BLOCKLEY, J. G., 1980, Tin deposits of Western Australia with special reference to the associated granites: Western Australia Geological Survey, Mineral Resources Bulletin 12, 184p.
- BUICK, R., THORNETT, J. R., McNAUGHTON, N. J., SMITH, J. B., BARLEY, M. E., and SAVAGE, M., 1995, Record of emergent continental crust ~3.5 billion years ago in the Pilbara Craton of Australia: *Nature*, v. 375, p. 574–577.
- CAMPANA, B., HUGHES, F. E., BURNS, W. G., WHITCHER, I. G., and MUCENIEKAS, E., 1964, Discovery of the Hamersley iron deposits (Duck Creek – Mt Pyrtou – Mt Turner areas): Australian Institute of Mining and Metallurgy, Proceedings, v. 210, p. 1–30.
- CHAMPION, D. C., and SMITHIES, R. H., 1998, Archaean granites of the Yilgarn and Pilbara Cratons. The Bruce Chappell Symposium: Granites, island arcs, the mantle and ore deposits, Abstract Volume: Australian Geological Survey Organisation, Record 1998/33, p. 4–25.
- CHAMPION, D. C., and SMITHIES, R. H., 2000, The geochemistry of the Yule Granitoid Complex, East Pilbara Granite–Greenstone Terrane; evidence for early felsic crust: Western Australia Geological Survey, Annual Review 1999–2000, p. 42–48.
- FERGUSON, K. M., and RUDDOCK, I., 2001, Mineral occurrences and exploration potential of the east Pilbara: Western Australia Geological Survey, Report 81, 114p.
- HICKMAN, A. H., 1983, Geology of the Pilbara Block and its environs: Western Australia Geological Survey, Bulletin 127, 268p.
- HICKMAN, A. H., 1990, Geology of the Pilbara Craton, in *Third International Archaean Symposium, Perth, W.A., 1990, Excursion Guidebook No. 5: Pilbara and Hamersley Basin edited by S. E. HO, J. E. GLOVER, J. S. MYERS, and J. R. MUHLING*: University of Western Australia, Geology Department and University Extension, Publication no. 21, p. 2–13.
- HICKMAN, A. H., 2000, Geology of the Dampier 1:100 000 sheet: Western Australia Geological Survey, 1:100 000 Geological Series Explanatory Notes, 39p.
- KOJAN, C. J., and HICKMAN, A. H., 1998, Late Archaean volcanism in the Kylene and Maddina Formations, Fortescue Group, west Pilbara: Western Australia Geological Survey, Annual Review 1997–98, p. 43–53.
- NELSON, D. R., 1997, Compilation of SHRIMP U–Pb zircon geochronology data, 1996: Western Australia Geological Survey, Record 1997/2, 189p.
- NELSON, D. R., 1998, Compilation of SHRIMP U–Pb zircon geochronology data, 1997: Western Australia Geological Survey, Record 1998/2, 242p.
- NELSON, D. R., 2000, Compilation of geochronology data, 1999: Western Australia Geological Survey, Record 2000/2, 251p.
- NELSON, D. R., 2001, Compilation of geochronology data, 2000: Western Australia Geological Survey, Record 2001/2, 205p.
- NELSON, D. R., 2002, Compilation of geochronology data, 2001: Western Australia Geological Survey, Record 2002/2, 282p.
- SMITHIES, R. H., and FARRELL, T. R., 2000, Geology of the Satirist 1:100 000 sheet: Western Australia Geological Survey, 1:100 000 Geological Series Explanatory Notes, 42p.
- SMITHIES, R. H., HICKMAN, A. H., and NELSON, D. R., 1999, New constraints on the evolution of the Mallee Basin, and their bearing on relationships between the contrasting eastern and western granite–greenstone terranes of the Archaean Pilbara Craton, Western Australia: *Precambrian Research*, v. 94, p. 11–28.
- THORNE, A. M., and TRENDALL, A. F., 2001, Geology of the Fortescue Group, Pilbara Craton, Western Australia: Western Australia Geological Survey, Bulletin 144, 249p.
- VAN KRANENDONK, M. J., 1998, Lithotectonic and structural map components of the North Shaw 1:100 000 sheet, Archaean Pilbara Craton: Western Australia Geological Survey, Annual Review 1997–98, p. 63–70.
- VAN KRANENDONK, M. J., 2003, Geology of the Tambourah 1:100 000 sheet: Western Australia Geological Survey, 1:100 000 Geological Series Explanatory Notes, 57p.
- VAN KRANENDONK, M. J., and PAWLEY, M. J., 2002, Tambourah, W.A. Sheet 2754: Western Australia Geological Survey, 1:100 000 Geological Series.
- VAN KRANENDONK, M. J., HICKMAN, A. H., SMITHIES, R. H., NELSON, D. R., and PIKE, G., 2002, Geology and tectonic evolution of the Archaean North Pilbara Terrain, Pilbara Craton, Western Australia: *Economic Geology*, v. 97, p. 695–732.
- WINGATE, M. T. D., 1999, Ion microprobe baddeleyite and zircon ages for Late Archaean mafic dykes of the Pilbara Craton, Western Australia: *Australian Journal of Earth Sciences*, v. 46, p. 493–500.

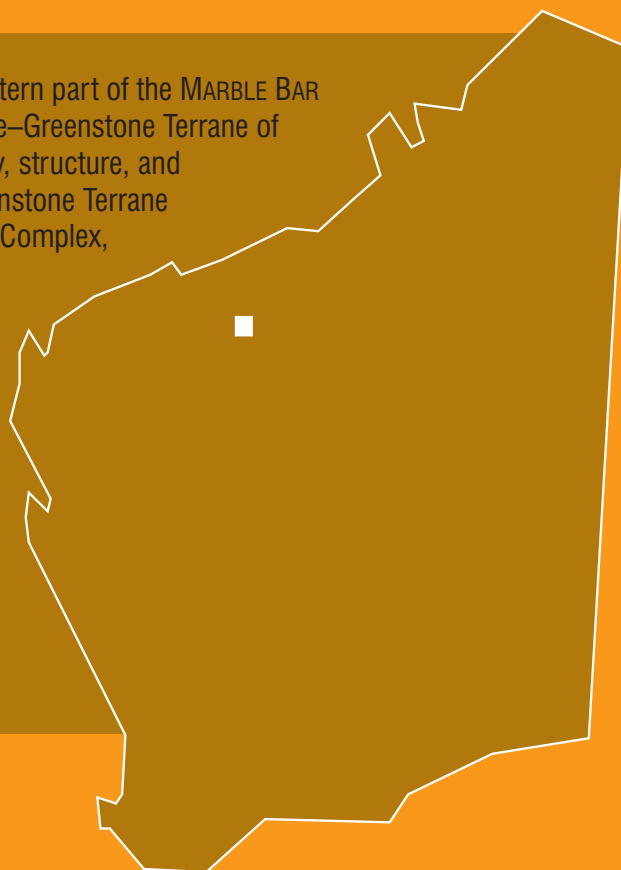
## Appendix

### Gazetteer of localities

| <i>Place name</i>       | <i>MGA coordinates</i> |                 |
|-------------------------|------------------------|-----------------|
|                         | <i>Easting</i>         | <i>Northing</i> |
| Cooletha Hill           | 694100                 | 7572600         |
| Logan Well              | 692100                 | 7607700         |
| Outcamp Well            | 690900                 | 7596800         |
| Tabletop Well           | 695500                 | 7591100         |
| White Springs Homestead | 687700                 | 7590000         |
| White Well              | 700500                 | 7616500         |
| White Ridge             | 691987                 | 7582606         |
| Woodstock Homestead     | 602600                 | 7608000         |
| Yandearra Outstation    | 660200                 | 7608000         |

The WHITE SPRINGS 1:100 000 sheet lies in the southwestern part of the MARBLE BAR 1:250 000 sheet within the Archaean East Pilbara Granite–Greenstone Terrane of the Pilbara Craton. These Notes describe the stratigraphy, structure, and mineralization of the area. The East Pilbara Granite–Greenstone Terrane is represented by the (c. 3420–2927 Ma) Yule Granitoid Complex, consisting of numerous generations of granitic rocks.

The granites contain xenoliths and roof pendants of unassigned greenstones. A younger component of the Pilbara Craton, the Hamersley Basin, is represented by the Late Archaean Fortescue Group. The Fortescue Group unconformably overlies the East Pilbara Granite–Greenstone Terrane, and consists of shallowly dipping and weakly metamorphosed volcanic and sedimentary rocks. The area has produced alluvial tin(–tantalum), zinc, and copper, and contains minor chrysotile asbestos deposits and serpentized peridotite with up to 60% chromite.



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