



Palaeoproterozoic crustal accretion and collision in the southern Capricorn Orogen: the Glenburgh Orogeny

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Abstract

The Capricorn Orogen in central Western Australia records the Palaeoproterozoic collision of the Archaean Pilbara and Yilgarn Cratons. Until recently only one orogenic event was thought to be the cause of this collision, the 1830–1780 Ma Capricorn Orogeny. However, recent work has uncovered an older event, the Glenburgh Orogeny that occurred between 2000 and 1960 Ma. The Glenburgh Orogeny reflects the collision of a late Archaean to Palaeoproterozoic microcontinent (the Glenburgh Terrane) with the Archaean Yilgarn Craton and is therefore tectonically distinct as well as significantly older than the widespread 1900–1800 Ma tectonothermal events recorded in northern Australia.

The Glenburgh Terrane preserves a different history from either the Yilgarn or Pilbara Cratons. Granitic gneiss protoliths dated at ca. 2550 Ma were intruded by widespread granite magmatism dated at 2005–1970 Ma, accompanied by high-grade metamorphism and deformation throughout the terrane. At ca. 1960 Ma silicic granite of the Bertibubba Supersuite intruded the northern margin of the Yilgarn Craton along the Errabiddy Shear Zone, a crustal-scale shear zone that today marks the contact of the Glenburgh Terrane and Yilgarn Craton. At ca. 1950 Ma silicic dykes intruded the southernmost part of the Glenburgh Terrane, marking the end of the Glenburgh Orogeny. East of the Glenburgh Terrane the Glenburgh Orogeny resulted in the cessation of mafic volcanism in the Bryah Basin, and the basin's eventual closure. Siliciclastic, carbonate and chemical sedimentary rocks were deposited in the Padbury Basin that formed a retro-arc foreland basin on top of the Bryah Basin, and probably records the later stages of the Glenburgh Orogeny collision.

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1. Introduction

The Capricorn Orogen is a zone of deformed and metamorphosed igneous and sedimentary rocks cut by granite intrusions that lies between the Archaean Yilgarn and Pilbara Cratons (Fig. 1). The age of the Capricorn Orogeny was previously loosely bracketed as 2200–1600 Ma by Rb–Sr and Sm–Nd age-dating

(Libby et al., 1986; Fletcher et al., 1983), but more recently has been constrained to 1830–1780 Ma by U–Pb sensitive high resolution ion microprobe (SHRIMP) dating (Occhipinti et al., 1999b). The Capricorn Orogeny has been interpreted as an intracratonic deformation event within a continuous Archaean basement (Gee, 1979; Windh, 1992), or, more recently, as the result of north–south convergence and subsequent collision of the Archaean Pilbara and Yilgarn Cratons (Tyler and Thorne, 1990; Myers, 1993; Myers et al., 1996). Krapez (1999) and

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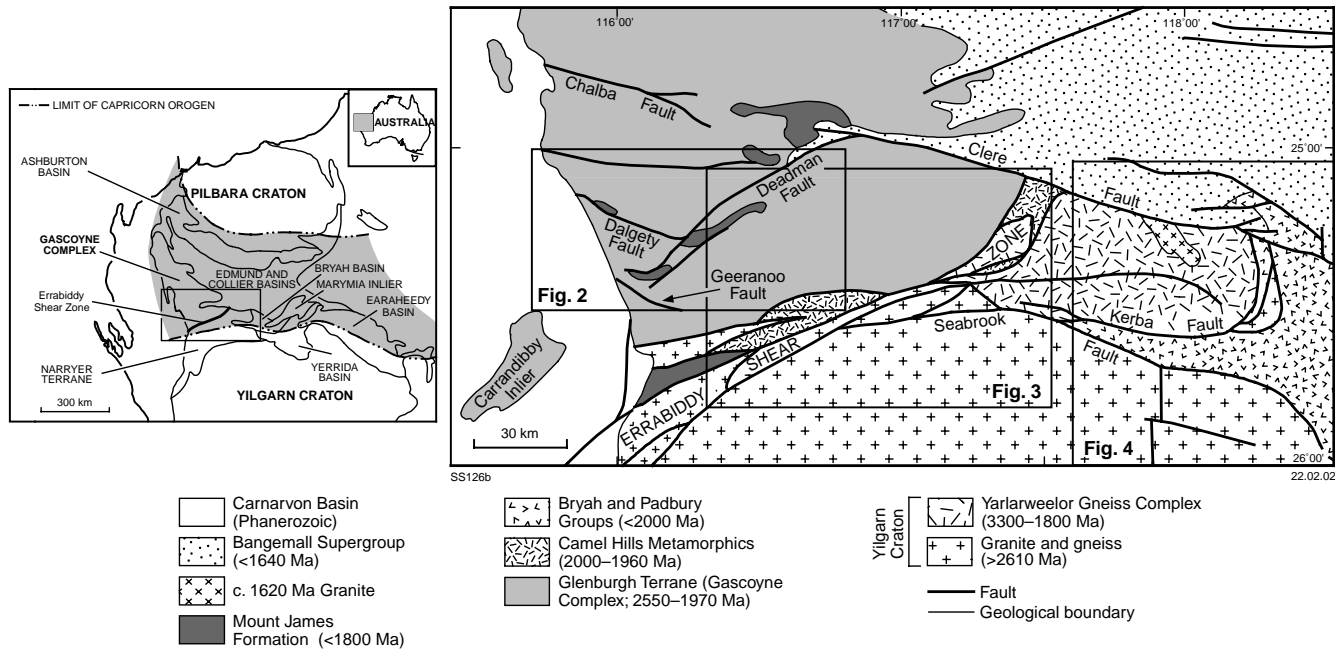


Fig. 1. Simplified regional geology maps of the main tectonic elements of the Western Australian Craton and the southern part of the Capricorn Orogen including the Glenburgh Terrane (Gascoyne Complex and including the Carrandibby Inlier), the Errabiddy Shear Zone, the Yarlaweelor Gneiss Complex, and the Bryah and Padbury Basins. The locations of Figs. 2–4 are outlined.

Krapez and Martin (1999) suggested that prior to the Capricorn Orogeny a rift developed within a larger craton at ca. 2045–1995 Ma, leading first to the development of oceanic crust, and then the onset of a southeast dipping subduction zone before regional-scale sinistral strike-slip movements at ca. 1815 or 1770 Ma. However, none of these previous models have considered an earlier orogenic event now recognised in the region—the Glenburgh Orogeny—which is a deformational, metamorphic and magmatic event that has been dated at 2005–1960 Ma by U–Pb SHRIMP geochronology (Occhipinti et al., 1999a; Sheppard et al., 2001a,b). This orogenic event probably reflects northwest–southeast or west–east accretion of a late Archaean to Palaeoproterozoic microcontinent to, or collision of the Pilbara–Gascoyne Craton (Sheppard et al., 2004) with, the Archaean Yilgarn Craton, forming the Errabiddy Shear Zone.

The Gascoyne Complex, which is a major tectonic unit within the Capricorn Orogen, is wedged between the Archaean Pilbara and Yilgarn Cratons and largely comprises variably deformed and metamorphosed granites, mafic to ultramafic igneous rocks, and sedimentary rocks. Until recently, the southern part of the Gascoyne Complex, referred to as the Glenburgh Terrane by Sheppard and Occhipinti (2000), was thought to contain a significant amount of deformed and metamorphosed Archaean rocks of the Narryer Terrane of the northwestern Yilgarn Craton (3730–2610 Ma) and some 1800–1600 Ma granite intrusions (Williams, 1986; Myers, 1990). Recent remapping and SHRIMP U–Pb zircon geochronology found that the granitic rocks in the Glenburgh Terrane can be divided into two main groups; ca. 2550 basement tonalite, granodiorite and monzogranites; and 2005–1970 Ma granitic rocks of the Dalgaringa Supersuite (Sheppard et al., 2004). Granites of the Dalgaringa Supersuite do not intrude the northwestern margin of the Yilgarn Craton. No rocks characteristic of those found in either the Archaean Yilgarn or Pilbara Cratons have been dated in the Glenburgh Terrane. This confirms that the Errabiddy Shear Zone forms the boundary between the Glenburgh Terrane and the northwest Yilgarn Craton (Fig. 1; Occhipinti et al., 1999b, 2001).

A hiatus in tectonothermal activity in the southern Capricorn Orogen occurred between ca. 1950 and 1830 Ma, that is between the end of the Glenburgh Orogeny and the start of the Capricorn Orogeny. Thus,

far no models for the development of the Capricorn Orogen have accounted for the Glenburgh Orogeny, the 1950–1830 Ma hiatus in tectonothermal activity in the region, and the lack of formation of arc-type magmatic rocks during and preceding, the 1830–1780 Ma Capricorn Orogeny.

Previous structural studies in the southern Capricorn Orogen (Fig. 1) have mainly focused on the Bryah and Padbury Basins (Hynes and Gee, 1986; Windh, 1992; Martin, 1994; Occhipinti et al., 1998b), although Williams (1986) presented an interpretation of the structure and metamorphism of the Gascoyne Complex, including its southern part—the Glenburgh Terrane. Various broad tectonic interpretations of the southern part of the Capricorn Orogen have been presented (Myers, 1993; Myers et al., 1996; Pirajno and Occhipinti, 2000) In this paper we describe the tectonic and temporal framework of the 2000–1960 Ma Glenburgh Orogeny.

2. Regional geology of the southern Capricorn Orogen

The southern part of the Capricorn Orogen (Fig. 1) contains variably exposed early to late Archaean granite and granitic gneiss, Palaeoproterozoic metasedimentary and mafic meta-igneous rocks, and Palaeoproterozoic granite and granitic gneiss. These units are locally overlain by Palaeoproterozoic to Mesoproterozoic sedimentary rocks. Four different tectonic units are recognised within the southern part of the Capricorn Orogen—the Glenburgh Terrane, the Errabiddy Shear Zone, the Yarlalweelor Gneiss Complex and the Bryah–Padbury basins (Figs. 1–4). The sequence of 2000–1950 Ma deformation, metamorphic and magmatic events within each of these units is outlined in Fig. 5.

The Yarlalweelor Gneiss Complex (Fig. 4) comprises 3300–2600 Ma granites, granitic gneiss and supracrustal rocks of the Narryer Terrane (Yilgarn Craton) that were locally deformed and intruded by biotite monzogranite of the 1965–1945 Ma Bertibubba Supersuite (Wooramel suite of Occhipinti et al., 1999b), and then metamorphosed, and deformed and intruded by voluminous granite at 1820–1780 Ma. The intrusion of ca. 1800 Ma granites was either sub-parallel or highly discordant with respect to gneissic

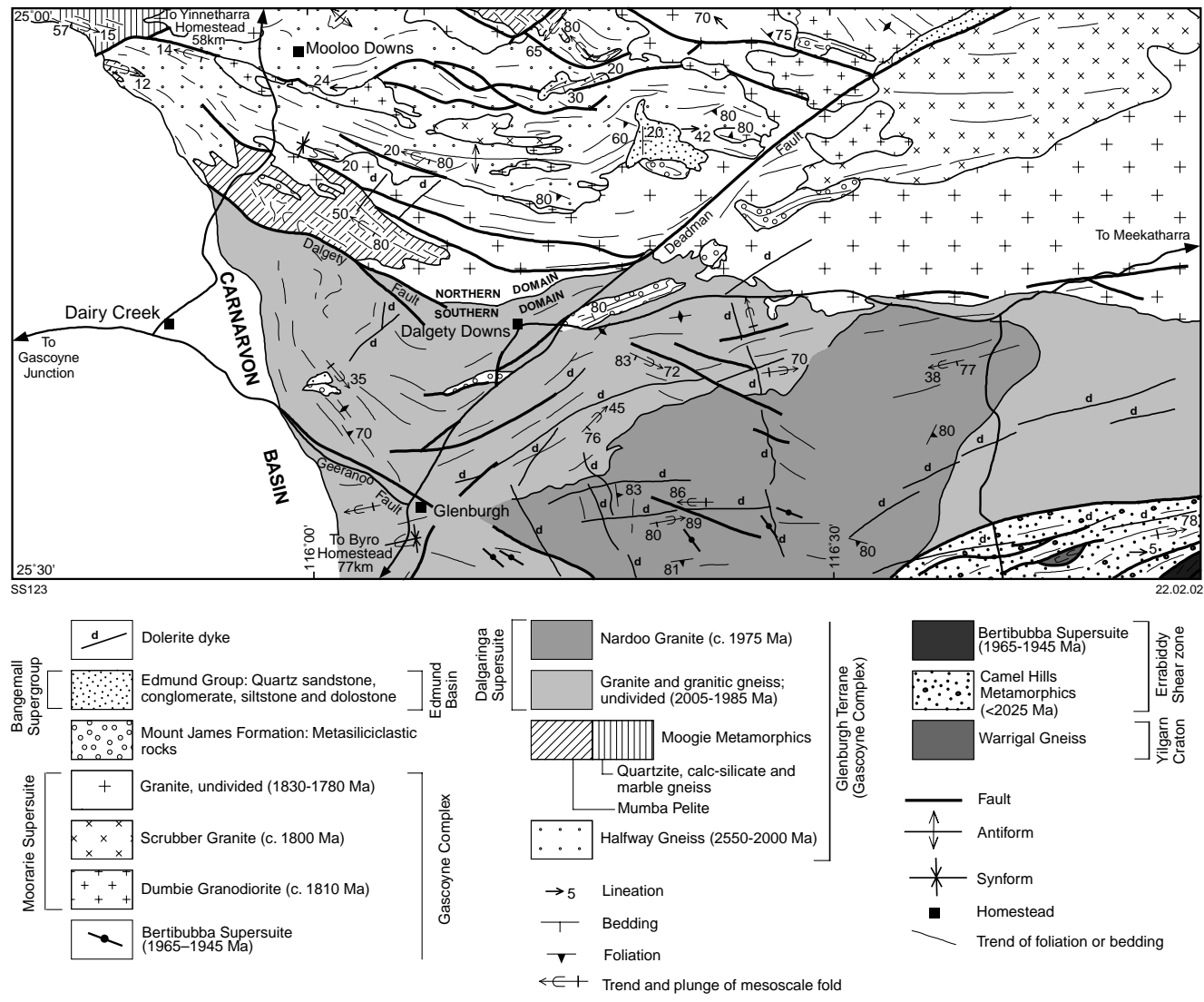


Fig. 2. Simplified map of the Glenburgh Terrane, showing the trend of folds and foliations in the region, and the northern domain (NGT) and southern domain (SGT).

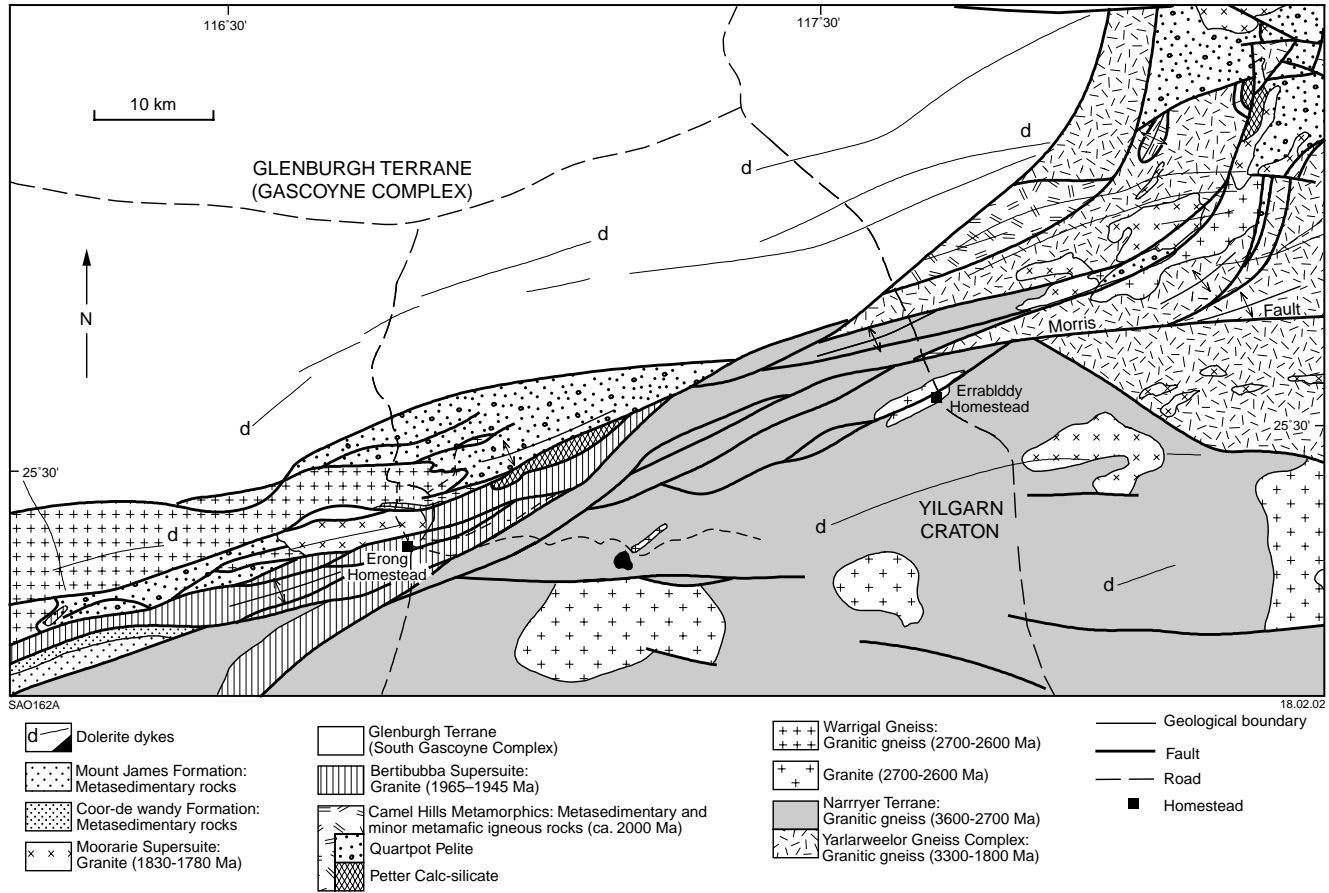
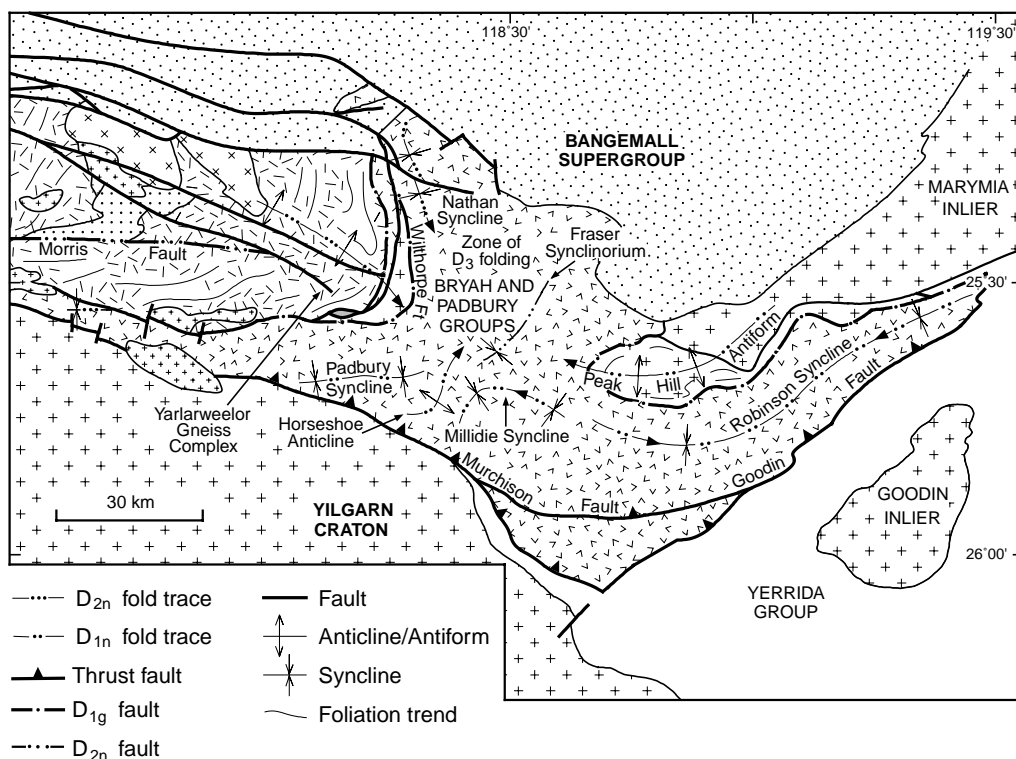


Fig. 3. Simplified geology map of the Errabiddy Shear Zone, showing the main tectonic units and structural trend.



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Fig. 4. Simplified map of the Yarlarweelor Gneiss Complex and Bryah and Padbury Basins area showing them main structural elements.

layering in Archaean granitic gneiss, and range from well foliated to massive and undeformed. The Yarlarweelor Gneiss Complex is in faulted contact with the low- to locally medium-grade ca. 2000 Ma sedimentary and mafic igneous rocks of the Bryah and Padbury Basins in the south and east. To the west, the Errabiddy Shear Zone cuts the Yarlarweelor Gneiss Complex and separates it from rocks of the Glenburgh Terrane.

The Glenburgh Terrane of the Gascoyne Complex consists of metamorphosed granitic rocks, and amphibolite, mafic granulite, pelitic schist, calc-silicate gneiss and dolomitic marble (Fig. 2). At ca. 2000 Ma tonalites, trondhjemites, monzogranites and granodiorites of the Dalgaringa Supersuite intruded into ca. 2550 Ma granodiorites, tonalites and monzogranites. In parts of the Glenburgh Terrane the ca. 2550 and 2000 Ma (Nelson, 2000; Occhipinti et al., 2001) granites were deformed and metamorphosed to form gneisses that are collectively termed the Halfway Gneiss (Occhipinti and Sheppard, 2001;

Occhipinti et al., 2001). Elsewhere, in the Glenburgh Terrane the Dalgaringa Supersuite mostly consists of 2005–1970 Ma granites that have been metamorphosed and heterogeneously deformed so as to locally form well-banded granitic gneiss. However, original igneous relationships between different phases of the supersuite can be observed in numerous low-strain zones. The older parts of the Dalgaringa Supersuite were metamorphosed and deformed by ca. 1989 Ma, and intruded by mesocratic and leucocratic tonalite at ca. 1975 Ma (Occhipinti and Sheppard, 2001). The granites of the Dalgaringa Supersuite have compositions similar to Phanerozoic subduction-related granites and may have formed in an Andean-type setting (Sheppard et al., 1999, 2003). Supracrustal rocks including mafic schist and gneiss, pelitic schist, calc-silicate gneiss and dolomitic marble, form distinct bands within the granitic gneiss units and are called the Moogie Metamorphics (Occhipinti and Sheppard, 2001).

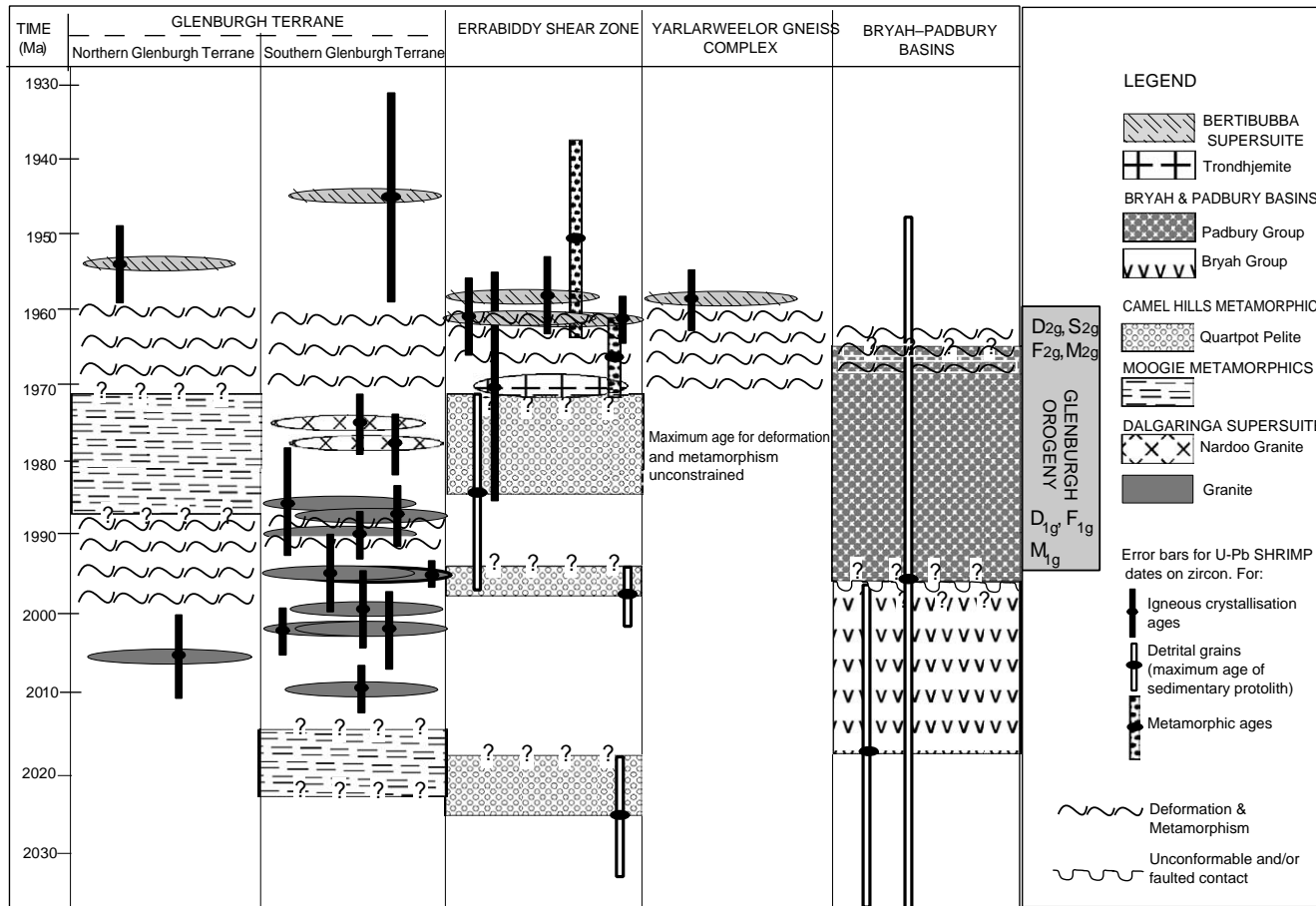


Fig. 5. Summary of 2000–1950 Ma geology in the southern Capricorn Orogen.

Xenocrystic zircons within rocks of the Dalgaringa Supersuite all have Palaeoproterozoic ages (Sheppard et al., 2004). However, in the northern part of the Glenburgh Terrane one sample of a 2550 ± 7 Ma meta-tonalite component of granitic gneiss of the Halfway Gneiss contained early and late Archaean xenocrystic zircons dated at ca. 2663–3300 Ma (Occhipinti et al., 2001), indicating that the Halfway Gneiss was at least in part derived from older Archaean rocks.

The Errabiddy Shear Zone separates the Yilgarn Craton from the Gascoyne Complex, and contains fault slices of both units, as well as the Yarlalweelor Gneiss Complex (Fig. 3). The shear zone also contains the Camel Hills Metamorphics—calc-silicate gneiss and pelitic schists and gneisses that are not present in other parts of the Capricorn Orogen. U–Pb SHRIMP age-dating of zircon from two samples indicates the pelitic schists were locally migmatized at 1966 ± 5 Ma and 1951 ± 13 Ma, and intruded by 1970 ± 15 Ma trondhjemite indicating that metamorphism of the pelitic schists and intrusion of the trondhjemite occurred over only a few million years (Occhipinti et al., 2001). Detrital zircons from within the pelitic schists are dominated by ca. 2250–2000 Ma ages, whereas within the calc-silicate gneisses, detrital zircons are mostly 2700–2608 Ma in age (Nelson, 1998). This indicates that the latest Archaean to Palaeoproterozoic parts of the Glenburgh Terrane were a possible source of sediment for the pelitic schists, whereas the Archaean Yilgarn Craton is a more likely source for the sedimentary protolith of the calc-silicate gneisses.

Well-foliated granite and pegmatite banded granitic gneiss of the Warrigal Gneiss are locally included as fault-bounded wedges in the Errabiddy Shear Zone. These granites have been dated at 2700–2600 Ma (Nelson, 2000; Occhipinti et al., 2001), similar to ages of late Archaean granites of the Narryer Terrane of the Yilgarn Craton.

The Bryah and Padbury Basins consist of the volcano-sedimentary Bryah and Padbury Groups, which were deposited along the northern margin of the Yilgarn Craton between 2000 and 1800 Ma (Occhipinti et al., 1998b; Pirajno and Occhipinti, 2000; Pirajno et al., 1998; Fig. 4). It has been suggested the basins may have developed in an intracratonic setting (Gee, 1979; Windh, 1992) although, more recently they have been interpreted to have

formed in an inter-cratonic setting, on a continental margin, or in a rift-setting (Krapez and Martin, 1999; Occhipinti et al., 1998b; Pirajno et al., 1998).

The Bryah Group contains metamorphosed and poly-deformed siliciclastic and chemical sedimentary rocks, together with voluminous mafic to ultramafic volcanic rocks, and minor intrusive rocks of the Narracoota Formation. The meta-mafic rocks locally contain pillow structures, sheeted dykes, a layered mafic-ultramafic igneous complex, sea-floor metasomatism and trace and rare-earth element geochemistry that support an oceanic crust model for their origin (Pirajno and Occhipinti, 2000; Pirajno et al., 1998). An area of mafic hyaloclastitic rocks in the southern part of the Bryah Basin suggests eruption of mafic lava in shallow waters, locally characterised by explosive activity, and it has been suggested it probably represents a proto-oceanic rift that separated the Marymia Inlier (a rifted part of the Yilgarn Craton; Fig. 4) from the Yilgarn Craton (Pirajno et al., 2004; Pirajno and Occhipinti, 2000). Pirajno and Occhipinti (2000) suggested that this rift was linked to back-arc opening during south-facing subduction, north of the Yilgarn Craton. After the cessation of oceanic volcanism, cooling resulted in thermal subsidence and basin development on top of the Narracoota Formation leading to the deposition of turbidites, and then finally chemical sedimentary rocks in the relatively shallow waters of a starved basin.

The Padbury Group consists of polydeformed and metamorphosed siliciclastic and chemical sedimentary rocks, which have been interpreted as developing in a retro-arc foreland basin (Padbury Basin) on top of the Bryah Group (Martin, 1994). The Padbury Group may record the convergence of the Glenburgh Terrane and the Yilgarn Craton.

The Yarlalweelor Gneiss Complex, Errabiddy Shear Zone, Glenburgh Terrane and the Bryah and Padbury Groups were variably metamorphosed and deformed during the 1830–1780 Ma Capricorn Orogeny. Felsic granites of the Moorarie Supersuite dated at 1830–1790 Ma intruded all four domains, although rocks of the Bryah and Padbury Groups were only locally intruded by granite close to their faulted contact with the Yarlalweelor Gneiss Complex (Martin, 1994; Reddy and Occhipinti, 2004). These granites were metamorphosed at high-grade within the Yarlalweelor Gneiss Complex (Occhipinti et al., 1998a), but in the

greenschist facies elsewhere in the southern Capricorn Orogen. Locally these granites are well foliated, and in some places sheets or dykes were folded.

3. Deformation and metamorphism

In the following discussion structural and metamorphic events are annotated according to the orogenic event during which they were formed, and numbered according to their relative age based on field relationships and/or their interpreted or bracketed age. Two main deformation events are recognised during the Glenburgh Orogeny— D_{1g} and D_{2g} (Figs. 2 and 5). Fabrics developed during the Glenburgh Orogeny were typically deformed during the Capricorn Orogeny and, in most domains, metamorphosed in the greenschist facies and locally overprinted during the 1070–750 Ma Edmondian Orogeny (Martin and Thorne, 2001). Fig. 5 summarizes the key structural and metamorphic elements, and magmatic events that developed between ca. 2000 and 1950 Ma in each of the tectonic units.

3.1. Glenburgh Orogeny

The Glenburgh Orogeny comprises two main deformation events: D_{1g} and D_{2g} (Figs. 2 and 5). The ages of these two events have been constrained in the southern part of the Glenburgh Terrane (SGT) by extensive SHRIMP U–Pb zircon dating on rocks that are either overprinted by, or cut the structural fabrics. The timing of the D_{2g} deformation event is also constrained in the Errabiddy Shear Zone by SHRIMP U–Pb dating. Elsewhere in the Capricorn Orogen, including the northern part of the Glenburgh Terrane (NGT), the ages of tectonic fabrics that developed prior to the Capricorn Orogeny have been less accurately determined; thus these fabrics can only be broadly correlated with those dated in the SGT.

Deformation during the Capricorn Orogeny was less intense in the SGT than in the other domains, allowing the older structural and metamorphic history to be unravelled. However, even in the SGT the older structural sequence can be difficult to discern, as the rocks have been heterogeneously deformed with the same structural elements not being developed everywhere.

3.1.1. D_{1g} structures and M_{1g} metamorphism

The earliest known deformation event (D_{1g}) of the Glenburgh Orogeny has been solely identified in the Glenburgh Terrane, and produced a foliation, S_{1g} . This early deformation fabric is associated with medium- to high-grade metamorphism (amphibolite to granulite facies; M_{1g} ; Occhipinti and Sheppard, 2001), and developed in the ca. 2550 and 2000 Ma granitic rocks, mafic gneisses and pelitic schists. Metamorphism outlasted deformation and locally granoblastic textures are strongly developed.

In the SGT an early foliation (S_{1g}) developed in some of the metamorphosed fine- to medium-grained ca. 2000 Ma granodiorites, tonalites and monzogranites. The granitoids are generally banded and contain an anhedral granoblastic texture. Locally in the southern most part of the SGT, meta-monzogranite dykes dated at 1987 ± 4 Ma (Occhipinti et al., 2001; Nelson, 1999) are sub-parallel to the easterly trending axial surfaces of tight to isoclinal, moderately plunging folds (correlated with the D_{1g} deformation event) in ca. 2000 Ma tonalite gneiss. Elsewhere in the SGT meta-diorite dykes in ca. 2000 Ma foliated granites, dated by SHRIMP U–Pb analyses of zircon at 1989 ± 3 Ma (Nelson, 1999), are sub-parallel to S_{1g} and have not been folded. Therefore, only local folding of S_{1g} occurred prior to ca. 1990 Ma and foliations in both ca. 1990 and 2000 Ma meta-granites are commonly sub-parallel. These structures either developed during a progressive D_{1g} deformation event (Fig. 5), or are a result of large-scale strain partitioning. Further work, including direct age-dating of metamorphic fabrics and detailed mapping, is required to solve this problem.

In the NGT, a gneissosity (S_{1g}) in the Halfway Gneiss is deformed about sub-horizontal to gently dipping folds. The axial surfaces of these folds are sub-parallel to flat or gently dipping D_{2g} faults that form the contact between the Halfway Gneiss and the Moogie Metamorphics. The development of the gneissic fabric is correlated with the D_{1g} deformation event in the southern domain and must have developed after 2006 ± 6 Ma (Occhipinti et al., 2001), which is the age of the youngest dated granitic component of the Halfway Gneiss, but before ca. 1800 Ma, the age of granite that cuts the gneiss.

The original trend of S_{1g} structures in the SGT is difficult to assess largely due to overprinting during

the Capricorn Orogeny; however, in the Carrandibby Inlier, the southwesternmost exposed part of the Glenburgh Terrane (Fig. 1), the rocks are largely unaffected by younger tectonism. Here meta-tonalite and meta-diorite sheets, which have igneous crystallisation ages of ca. 2002 Ma (Nelson, 2000), are steeply to vertically dipping and northerly trending. In addition, axial surfaces of isoclinal folds in a pegmatite banded granitic gneiss, with a precursor granite age of ca. 2500 Ma (Occhipinti et al., 2001), are also northerly trending and steeply dipping.

The presence of mafic granulites, strips of migmatitic pelitic granulite within metagranites and granitic gneisses of the Dalgaringa Supersuite in the central part of the SGT, indicates that these rocks locally were metamorphosed at high grade during D_{1g} (Occhipinti and Sheppard, 2001). However, these high-grade conditions were not recorded everywhere, with amphibolite facies assemblages dominant in the SGT. The amphibolite facies rocks are not the product of retrogression of the granulite facies rocks, as no relict granulite facies minerals or textures indicative of higher grade are present. Rocks metamorphosed under both amphibolite facies and granulite facies conditions were juxtaposed after M_{1g} .

3.1.2. D_{2g} structures and M_{2g} metamorphism

The second regional deformation event, D_{2g} is associated with a metamorphic event M_{2g} , and is recognised in the Glenburgh Terrane, the Errabiddy Shear Zone, parts of the Yarlalweelor Gneiss Complex, and possibly in the Bryah and Padbury Basins.

3.1.2.1. Glenburgh Terrane. In the SGT mesoscopic upright folds (F_{2g}) are widespread. Most of the folds are tight or isoclinal, but in local zones of low D_{2g} strain they are open to close. The F_{2g} folds trend westerly or southwesterly, and plunge moderately to very steeply to the east and northeast or to the west and southwest. However, these folds probably originally developed as northerly or northeasterly trending structures (Occhipinti and Sheppard, 2001), and have been re-orientated during the Capricorn Orogeny. The possible northerly or northeasterly trend for the D_{2g} fabrics in the Glenburgh Terrane can be seen in the Carrandibby Inlier in the SGT in which the Capricorn Orogeny has had little effect. In addition the trend

of ca. 1950 Ma granitic dykes, which cut D_{1g} and D_{2g} deformation fabrics, changes from east or south-easterly trending in the Carrandibby Inlier (Fig. 1) to south–southeasterly trending in the south–central part of the SGT, also reflecting this re-orientation.

The first regional foliation in the Moogie Metamorphics within the NGT, is a sub-horizontal to gently dipping foliation, correlated with S_{2g} . This foliation developed sub-parallel to bedding forming a composite S_0/S_{2g} fabric and is associated with a medium-grade M_{2g} metamorphic event. The S_{2g} foliation is also axial planar to sub-horizontal folds (F_{2g}) of bedding observed in the Moogie Metamorphics where they deform quartzite (Fig. 6a), and of locally well-developed S_{1g} in the Halfway Gneiss, e.g. east of 2 mile bore (at MGA 405800E 7229350N; Fig. 6b).

In the NGT some well-developed easterly trending stretching lineations and S_{2g} foliations are indicative of mylonitic development. The stretching lineations are generally sub-parallel to the fold axis of a west–northwesterly regional-scale antiform that developed during the Capricorn Orogeny (Occhipinti and Sheppard, 2001). The fold axis of the antiform ranges from sub-horizontally plunging to steeply plunging, probably due to later re-folding (Occhipinti and Sheppard, 2001).

In thin-sections oriented parallel to the stretching lineation and normal to the foliation, the fabric is usually symmetric, including feldspar augen, but locally asymmetric augens and shear bands are present. In the central part of the NGT asymmetric structures observed in the field and in thin section indicate top-to-the-west or northwest movement. In the northern part of the NGT within the Halfway Gneiss both rotated feldspar porphyroblasts and some S–C fabrics indicate possible top-to-the-northwest shear sense or south-over-north movement. Flat D_{2g} faults represented by mylonite zones between the Halfway Gneiss and the Moogie Metamorphics are also present within the region.

In some areas, particularly in the Moogie Metamorphics north of the Dalgety Fault (Fig. 2) in the NGT, massive quartz veins up to several kilometres long trend sub-parallel to the S_0/S_{2g} fabric in micaceous metasedimentary rocks, and the contacts between the Moogie Metamorphics and the Halfway Gneiss. These units are commonly well foliated and may be veins, or deformed and metamorphosed quartz sandstone.

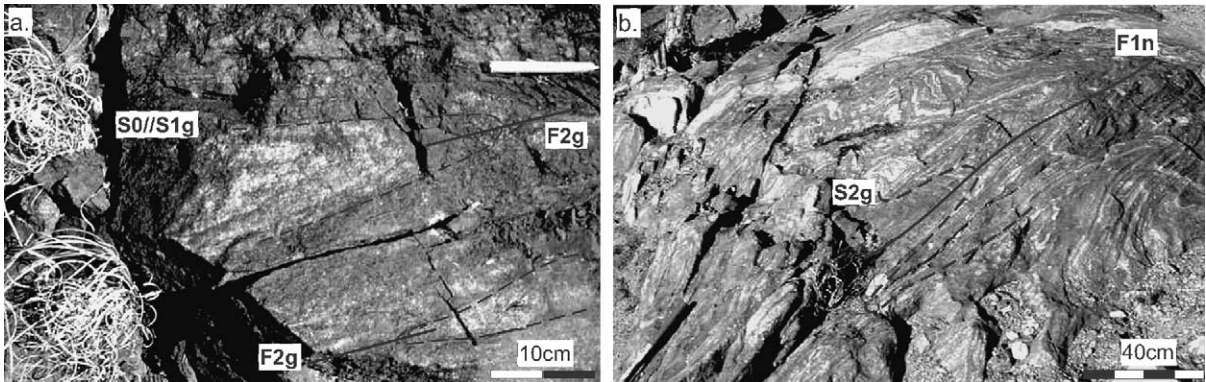


Fig. 6. Photographs of the early structures in the Moogie Metamorphics and the Halfway Gneiss. (a) Sub-horizontal to gently inclined isoclinal fold in quartzite from (MGA 380380E 7233100N). (b) Folds in the Halfway Gneiss. S_{1g} is folded about isoclinal folds and is transposed into S_{2g} which is refolded into upright F_{1n} folds. The F_{1n} fold plunges moderately to the east.

Where they are veins they intruded sub-parallel to D_{2g} structures and fabrics, for example, the S_{2g} foliation in the Halfway Gneiss and F_{2g} sub-horizontal folds in quartzite of the Moogie Metamorphics, and may represent D_{2g} sub-horizontal detachment surfaces.

As mentioned previously the mylonitic fabric with easterly-trending stretching lineations and flat faults as well as the D_{2g} sub-horizontal detachment surfaces in the Moogie Metamorphics, are deformed around a regional-scale Capricorn-age fold. In addition the stretching lineations are sub-parallel to the hinge lines of mesoscale parasitic folds to the large-scale Capricorn-age antiform. This may be because the shear zone in which the mylonite developed had the shape of an easterly trending (more open?) fold, which was subsequently tightened. However, it is unlikely that the mylonite formed in its present geometrical orientation as folds parallel to the lineation are too tight to be mechanically possible as corrugations in an active mylonite zone. Therefore, it is more likely that the shear zone was affected by N–S shortening after development of the shallow mylonitic fabric—that is during the Capricorn Orogeny.

The Mumba Pelite was probably metamorphosed at medium-grade (amphibolite facies) during M_{2g} ; however, the M_{2g} mineral assemblages in the Mumba Pelite are typically completely overprinted (generally pseudomorphed) by lower grade mineral assemblages (Occhipinti and Sheppard, 2001). Locally garnet is partially or completely pseudomorphed by chloritoid and chlorite, and chlorite may have pseudomorphed

biotite. In addition mats of sericite appear to represent completely pseudomorphed sillimanite or staurolite.

During D_{2g} a penetrative foliation developed in the ca. 1975 Ma Nardoo Granite, which intruded the 2005–1989 Ma components of the Dalgaringa Supersuite in the SGT. The S_{2g} foliation is defined by elongate biotite or, in places, by lenses and veins of pegmatite up to a few centimetres wide forming a gneissosity. Clots of fine-grained biotite after garnet are typically developed in this gneissosity. The D_{2g} deformation event occurred prior to ca. 1950 Ma, the age of granitic dykes that cut the S_{2g} foliation in the Nardoo Granite (Occhipinti and Sheppard, 2001).

The effects of M_{2g} are commonly difficult to differentiate from M_{1g} (Occhipinti and Sheppard, 2001). Mafic granulites, and amphibolites with M_{1g} assemblages contain little evidence of M_{2g} , probably because of local anhydrous conditions during M_{2g} . Mineral assemblages formed during M_{2g} in the meta-granites consist of biotite, oligoclase–andesine, and epidote. Locally garnet and hornblende are also present. The composition of the plagioclase (oligoclase–andesine) together with the presence of epidote, suggests that the rocks were metamorphosed in the epidote–amphibolite zone (transitional between the amphibolite and greenschist facies) (Miyashiro, 1994). High-grade assemblages in calc-silicate gneisses and marbles that formed during M_{1g} are overprinted by lower grade assemblages (Occhipinti and Sheppard, 2001). For example, in the amphibole- and diopside-rich gneisses, pargasite and diopside

show incipient replacement along rims and fractures to tremolite, and plagioclase is partially replaced by clinozoisite and a more sodic plagioclase.

During the Capricorn Orogeny in the NGT, apart from the Halfway Gneiss and Moogie Metamorphics being folded into a regional-scale antiform, only local development of a pervasive greenschist facies crenulation cleavage (developed sub-parallel to these fold axial surfaces) and retrogression of higher grade mineral assemblages occurred (Occhipinti and Sheppard, 2001).

3.1.2.2. Errabiddy Shear Zone. The Errabiddy Shear Zone (Figs. 1 and 3) initially developed during the 2000–1960 Ma Glenburgh Orogeny (Occhipinti et al., 1999a). Precursor sedimentary and minor mafic rocks of the Quartpot Pelite and Petter Calc-silicate of the Camel Hills Metamorphics, and granite protoliths to the Warrigal Gneiss, were deformed and metamorphosed prior to ca. 1960 Ma before being folded into upright, tight to isoclinal, easterly trending folds during the Capricorn Orogeny. In the Camel Hills Metamorphics and Warrigal Gneiss a metamorphic foliation, which is locally gneissic or contains a flaser texture, developed during the Glenburgh Orogeny. This foliation, which is now steeply dipping, was originally sub-horizontal or shallowly dipping and probably northerly or northeasterly trending. The foliation is sub-parallel to faulted contacts between some outcrops of the Warrigal Gneiss and the Camel Hills Metamorphics, which are thought to have developed during D_{2g} tectonic interleaving within and between these units (Fig. 5).

A sub-horizontal to moderately plunging mineral lineation, largely defined by fine-grained biotite, but locally defined by white mica, is locally well developed on the S_{2g} foliation plane and may have developed during D_{2g} . This mineral lineation generally trends parallel to the fold axes of regional-scale upright, tight to isoclinal folds. These upright folds developed post D_{2g} , during the Capricorn Orogeny (Sheppard and Occhipinti, 2000). In the central part of the shear zone, the mineral lineation (defined by biotite or white mica) is westerly, to west-southwesterly trending whereas similar mineral lineations are south- or north-trending in the northeastern part of the shear zone. Field observations and thin-section analyses of rocks in the central part of the shear

zone, around Erong Homestead (Fig. 3) indicates that the sub-horizontally to moderately plunging lineations are associated with dextral strike-slip movements. These mineral lineations post-date ca. 1960, and could be significantly younger (cf. Reddy and Occhipinti, 2004). In the areas adjacent to, and north-east of Errabiddy Homestead (Fig. 3), sub-horizontally to moderately plunging mineral lineations are also associated with dextral strike-slip movement; however, it is not clear whether these are related to the Glenburgh Orogeny or subsequent deformation. To the east, Reddy and Occhipinti (2004) found that kinematic indicators that formed along the post-ca. 1800 Ma Kerba Fault (a splay off the Errabiddy Shear Zone) consistently illustrated dextral strike-slip movement, regardless of whether a mineral lineation was present or not.

The Camel Hills Metamorphics outcrop as fault-bounded blocks throughout the exposed extent of the Errabiddy Shear Zone. Metamorphic mineral assemblages developed in gneissic banding (S_{2g}) within the Camel Hills Metamorphics during D_{2g} , indicate that M_{2g} was a medium- to high-grade event. Locally pelitic and semi-pelitic schist and gneiss of the Quartpot Pelite were migmatized during D_{2g} (Fig. 7a; Occhipinti and Sheppard, 2001). S_{2g} is a differentiated foliation that is largely defined by the alignment of sillimanite and biotite (although sillimanite is generally pseudomorphed by fine-grained sericite mats) and quartz-plagioclase domains. Garnet does not contain inclusion trails but is either wrapped by, or overprints the S_{2g} foliation, thus it most likely crystallised synchronously with, or just after D_{2g} . Garnet porphyroblasts are commonly partially or completely pseudomorphed by chloritoid or chlorite, and are also commonly replaced along rims and fractures by fine-grained biotite, muscovite and quartz.

The southwestern-most outcrops of semi-pelitic or psammitic rocks of the Quartpot Pelite (Fig. 3) have been metamorphosed in the amphibolite facies but did not attain the metamorphic conditions required for migmatization. This reflects either a decrease in metamorphic grade or a lower a_{H_2O} , during M_{2g} from northeast to southwest along the Errabiddy Shear Zone. The resulting metamorphic isograd between the migmatized and unmigmatized rocks was folded into an upright easterly trending fold during the Capricorn Orogeny (D_{1n}).

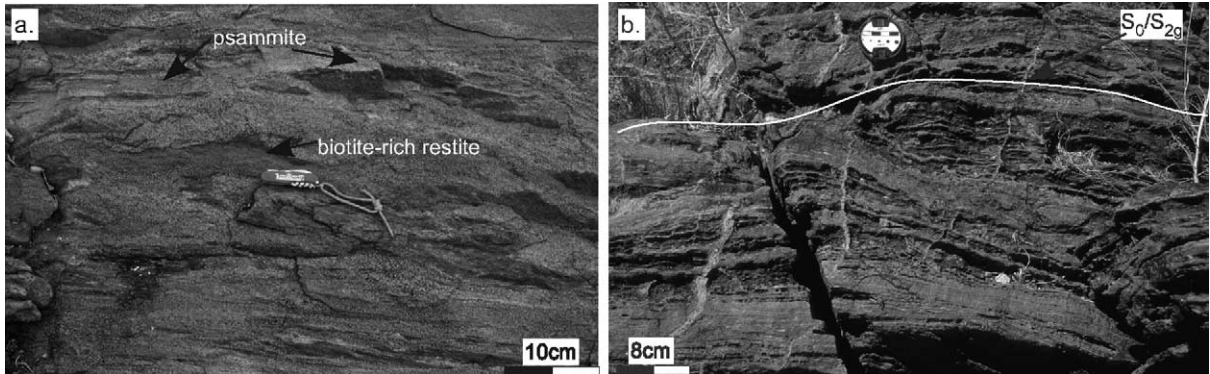


Fig. 7. Photographs of the Camel Hills Metamorphics. (a) Migmatitic gneiss of the Camel Hills Metamorphics with refractory psammite and biotite-rich material; (b) calc-silicate gneiss with a boudinage composite S_0/S_{2g} fabric.

The Petter Calc-silicate consists of calc-silicate schist and gneiss, para-amphibolite and biotite-rich schist, which contain a well-developed S_{2g} foliation. The foliation has parallel to fine, 1 mm to 1 cm thick compositional layering interpreted as original bedding, thus forming a composite S_0/S_{2g} fabric, which is commonly boudinaged (Fig. 7b).

Some Archaean rocks of the northwestern margin of the Yilgarn Craton caught up in the Errabiddy Shear Zone during the D_{2g}/M_{2g} event were intruded by granite sheets and plutons of the ca. 1960 Ma Bertibubba Supersuite at the end of the Glenburgh Orogeny. Locally, granites of the Bertibubba Supersuite are foliated and folded (Sheppard and Swager, 1999; Occhipinti et al., 2001); however, the age of the fabrics in these granites has not been directly determined, and the granites may have remained undeformed until the Capricorn Orogeny.

During the Capricorn Orogeny, tight, upright, shallow to steeply plunging folds deformed the sub-horizontally dipping S_{2g} foliation in the Camel Hills Metamorphics. Pervasive retrogression of upper amphibolite facies assemblages, which formed during M_{2g} , to greenschist facies assemblages in the Camel Hills Metamorphics also took place (Sheppard and Occhipinti, 2000). In the western and central parts of the Errabiddy Shear Zone these folds are westerly trending, whereas in the eastern and northern part of the shear zone, they are northeasterly to northerly trending (Sheppard and Occhipinti, 2000; Occhipinti et al., 2001). These folds were refolded during the later stages of the Capricorn Orogeny,

due to east–southeasterly trending dextral strike–slip movement (Sheppard et al., 2003), and north–south compression.

3.1.2.3. Yarlalweelor Gneiss Complex. The Yarlalweelor Gneiss Complex is in faulted contact with the Bryah and Padbury Groups (Fig. 4). The gneiss complex mainly comprises Archaean granitic gneisses that were reworked during the Palaeoproterozoic. Although it is clear that most of the folds and faults developed in the gneiss complex formed during the Capricorn Orogeny (Occhipinti et al., 1998a; Sheppard and Swager, 1999), it is unclear whether structures related to the Glenburgh Orogeny were well developed throughout the complex. However, a folded foliation in the ca. 1960 Ma Yamagee Granite (of the Bertibubba Supersuite) is older than foliations which developed in younger Capricorn-age granites in the region (Sheppard and Swager, 1999) and may have developed soon after the granite formation, during the waning stages of the Glenburgh Orogeny.

The most dominant structures in the Yarlalweelor Gneiss Complex are tight, upright shallow to steeply plunging folds that developed during the Capricorn Orogeny. As in the Errabiddy Shear Zone, these folds were refolded during later stages of the Capricorn Orogeny, due to east–southeasterly trending dextral strike–slip movement (Sheppard et al., 1999; Occhipinti et al., 1998a), and north–south compression. In the Yarlalweelor Gneiss Complex, this appears to have accompanied a transition from ductile to brittle conditions in the region (Occhipinti and Myers, 1999).

3.1.2.4. Bryah–Padbury Basins. The earliest deformation event in the Bryah Group is present in the Peak Hill Antiform area and is correlated with D_{2g} (Fig. 4). It is represented by layer-parallel mylonitic thrust faults and by folds that were probably sub-horizontal prior to subsequent deformation. In addition, D_{2g} isoclinal folds developed in banded iron-formations (for example, the Robinson Syncline; Fig. 4). These faults and folds were all overprinted during the Capricorn Orogeny by D_{1n} upright east-west striking regional folds. This contrasts with the interpretation of Occhipinti et al. (1998b) who suggested that D_1 and D_2 structures (now regarded as D_{2g} and D_{1n} , respectively) could be interpreted as successive stages of progressive deformation of the Bryah and Padbury Groups.

During both the Glenburgh and Capricorn Orogenies, the Bryah and Padbury Groups were tectonically interleaved with the Yarlarweelor Gneiss Complex (Fig. 4), and during the Capricorn Orogeny they were intruded by granite (Martin, 1994; Reddy and Occhipinti, 2004) in areas close to the gneiss complex.

The highest grade metamorphic mineral assemblages in the Bryah and Padbury basins are found in the contact zones between the Yarlarweelor Gneiss Complex and the overlying metasedimentary rocks of the Padbury Group (Occhipinti et al., 1998; Fig. 4). East of the Yarlarweelor Gneiss Complex, a northerly trending strip of metamorphosed arkosic sandstone of the Padbury Group contains amphibolite facies mineral assemblages. Metamorphism in the Bryah and Padbury Groups generally does not exceed greenschist facies. The relationships between metamorphic mineral growths and deformation are summarised in Pirajno et al. (2000).

4. Tectonic models

Tectono-magmatic events observed across the Glenburgh Terrane, Errabiddy Shear Zone, Yarlarweelor Gneiss Complex and Bryah–Padbury basins have been correlated temporally, using available U–Pb SHRIMP geochronological data (Fig. 5). The nature and ages of these elements are used to propose tectonic models for the southern Capricorn Orogen.

The tectonic setting of the Gascoyne Complex is still poorly understood, and previous models do

not take into account the 2000–1970 Ma Glenburgh Orogeny (Occhipinti et al., 1999b), and incorrectly suggested the complex contained reworked crust from the Yilgarn Craton (Williams, 1986; Myers, 1990; Muhling, 1990). However, the southern Gascoyne Complex consists of Palaeoproterozoic foliated and gneissic granites of the Dalgaringa Supersuite, and low- to medium-grade metasedimentary rocks of the Moogie Metamorphics (Occhipinti and Sheppard, 2001) of the Glenburgh Terrane. Basement to these rocks is probably represented by tectonically interleaved latest Archaean (ca. 2550 Ma) gneissic granite, which now makes up much of the Halfway Gneiss. The Archaean granite components of the Halfway Gneiss are younger than any dated Archaean granites from the Pilbara or Yilgarn Cratons, and their ϵ_{Nd} values plot outside of the field of granites of the Narryer Terrane (Yilgarn Craton) (Sheppard et al., 2004). In addition, the Archaean component of the Halfway Gneiss is mostly granodioritic or tonalitic in composition, which is more mafic than the monzogranite and syenogranite that dominates the Yilgarn Craton. Thus, the Glenburgh Terrane is exotic to the Yilgarn Craton, and to the Pilbara Craton which was cratonised prior to ca. 2770 Ma (Fig. 1).

In the southern Capricorn Orogen, magmatism between 2005 and 1970 Ma only took place in the Glenburgh Terrane, suggesting that the Glenburgh Terrane formed a separate terrane from rocks in the Errabiddy Shear Zone, the Yarlarweelor Gneiss Complex, and the Bryah and Padbury Basins at this time. This interpretation is supported by the restriction of high-grade metamorphism during D_{1g} to the Glenburgh Terrane, implying that it was not metamorphosed in its present location. The 2005–1970 Ma Dalgaringa Supersuite which is dominated by diorite, tonalite and granodiorite, contrasts in composition to most Palaeoproterozoic batholiths of northern Australia, which largely consist of monzogranite and granodiorite (Wyborn et al., 1992). Major and trace element compositions of granites of the Dalgaringa Supersuite are similar to Phanerozoic subduction-related granites suggesting that the supersuite may have formed in an Andean-type setting (Sheppard et al., 1999) along the margin of a late Archaean to Palaeoproterozoic continent or microcontinent (Fig. 8). It is likely that the Dalgaringa Supersuite developed at about the same time as the Bryah and Padbury basins, but to the west

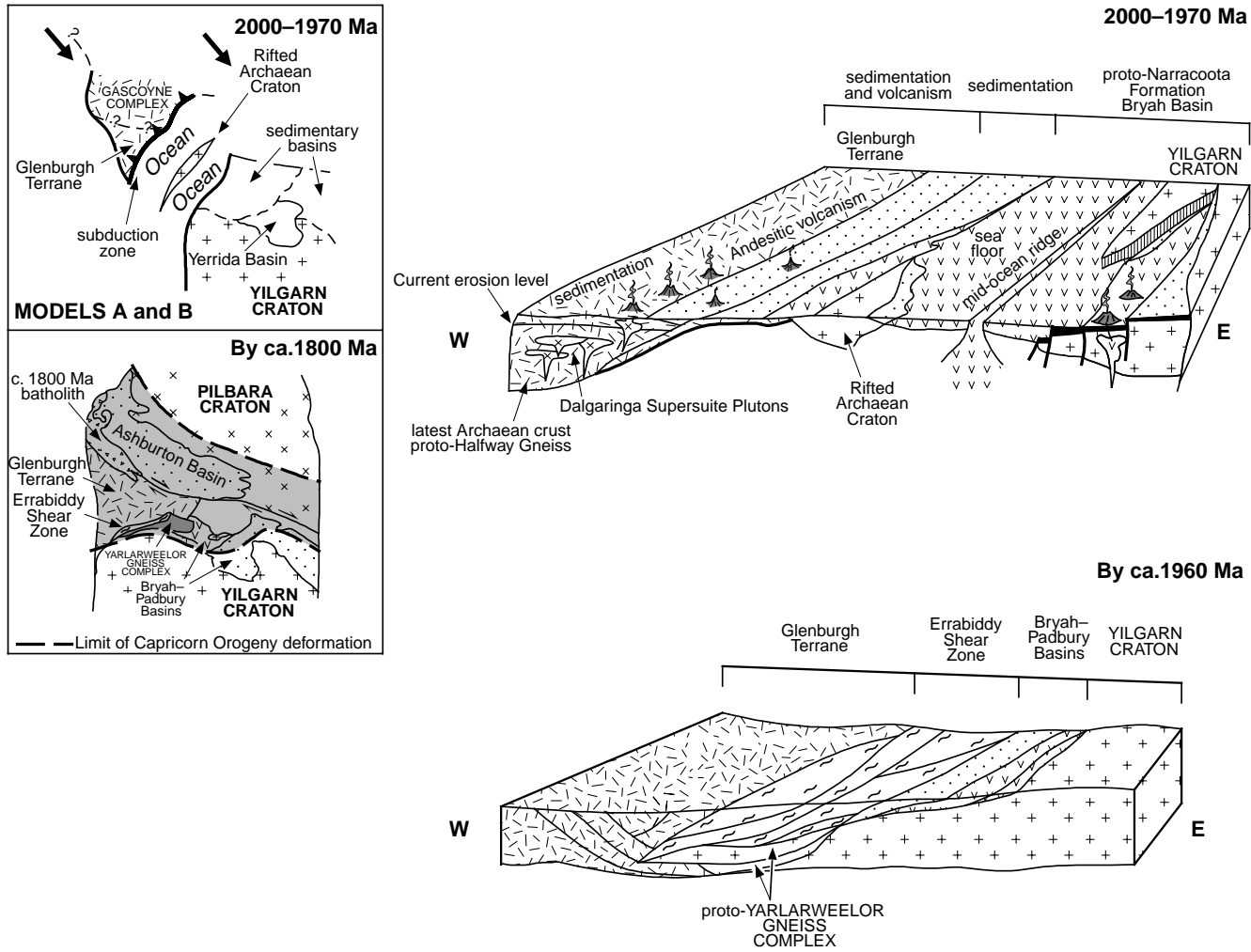


Fig. 8. Schematic diagram illustrating the possible tectonic evolution of the southern Capricorn Orogen during the Glenburgh Orogeny. The bottom inset of the Capricorn Orogen shows the effects of the ca. 1800 Ma Capricorn Orogeny in the region, which is largely reflected by the current-day geometry of the southern Capricorn Orogen.

(Fig. 8). However, Dalgaringa Supersuite rocks locally contain an extra structural fabric, which records an earlier deformation and metamorphism event than is observed in the Bryah and Padbury Basins, Yarlalweelor Gneiss Complex and rocks in the Errabiddy Shear Zone. This could be due to either syn-magmatic deformation, or regional migration of deformation and metamorphism from west to east, thus beginning in the Glenburgh Terrane.

Sedimentary protoliths to the Camel Hills Metamorphics were sourced from both the Yilgarn Craton, and from now, unexposed, early Palaeoproterozoic crust. It is possible that these protoliths were deposited in different basin-settings between the converging Glenburgh Terrane and rifted part of the Yilgarn Craton (Fig. 8). In this case the proto-Quartpot Pelite may have been deposited as an accretionary prism, whilst the proto-Petter Calc-silicate may have been deposited in a carbonate shelf or platform over and west of a possible rifted part of the Yilgarn Craton.

The Bryah and Padbury Basins are poorly dated; however, limited geochronological data on the Bryah and Padbury Groups and cross-cutting relationships with younger (ca. 1800 Ma) granite (Martin, 1994) suggest that they were deposited by ca. 2000 Ma. Pirajno and Occhipinti (2000), Myers (1993) and Myers et al. (1996) suggest that the Bryah Basin was a back-arc basin formed during subduction beneath the northern margin of the Yilgarn Craton. However, remnants of cordilleran-like magmatic suites have not been identified to the north of the Bryah and Padbury Basins, although they may be buried beneath the Mesoproterozoic Edmund and Collier Basins of the Bangemall Supergroup.

Meta-hyaloclastites in the southern part of the Bryah Basin appear to have erupted in a shallow-water setting and were emplaced on the Yilgarn crust (Pirajno and Occhipinti, 2000), contrasting with the oceanic setting of the metabasites of the Narracoota Formation. Following the cessation of mafic volcanism, thermal subsidence and rift development led to the deposition of turbidites, followed by chemical sedimentary rocks in a starved basin (Pirajno and Occhipinti, 2000).

The Padbury Group was deposited over the Bryah Group in the Padbury Basin, east of the proto-Errabiddy Shear Zone. The Padbury Group, which

consists of metamorphosed siliciclastic, carbonate and chemical sedimentary rocks, is interpreted as a retro-arc foreland basin, which recorded a collision (Martin, 1994; Fig. 8). The age of the Padbury Group is poorly constrained; however, in places, it unconformably overlies the Bryah Group (Martin, 1994), and deformed rocks of the Padbury Group are intruded by granite (Martin, 1994) that are correlated with ca. 1800 Ma granites in the region. If so, the Padbury Basin would have formed prior to the 1830–1780 Ma Capricorn Orogeny, and most likely during the 2000–1960 Ma Glenburgh Orogeny. At this time, rocks of the Bryah and Padbury Groups were also deformed into sub-horizontal structures (correlated with regional D_{2g}), and parts of the Bryah Group were thrust over the passive margin of the Yilgarn Craton from west to east.

Previous models for the development of the Bryah and Padbury Basins, including Pirajno et al. (1998) and Myers (1993), and in part Pirajno and Occhipinti (2000) inferred that these basins developed north of the Yilgarn Craton, during the Capricorn Orogeny, and were deformed by it. The Bryah and Padbury Basins, more likely, developed to the west or northwest of the Yilgarn Craton (Fig. 8) during the Glenburgh Orogeny. This would explain the apparent progression from west to east of rifting throughout the basin suggested by Pirajno and Occhipinti (2000). In this case the northwestern, or western margin of the Yilgarn Craton would have rifted (prior to ca. 2000 Ma) in order to produce the oceanic crust (Pirajno and Occhipinti, 2000), which is the setting of the Narracoota Formation (Fig. 8).

By ca. 1960 Ma, the Glenburgh Terrane microcontinent had collided with the passive margin of the Yilgarn Craton, with both now juxtaposed along the Errabiddy Shear Zone (Fig. 8). Felsic magmatism only took place in the rifted portion of the Yilgarn Craton, which included the proto-Yarlalweelor Gneiss Complex, and the Camel Hills Metamorphics. The Camel Hills Metamorphics and any possible rifted fragments of the Yilgarn Craton (possibly some protolith granites to the Warrigal Gneiss?) were metamorphosed and deformed by this time, and included in the Errabiddy Shear Zone (Fig. 8). Sheppard et al. (2003) suggested that the Glenburgh Terrane was subducted beneath the Yilgarn Craton during the Glenburgh Orogeny, because Nd-isotope data show that

the 1965–1945 Ma granite plutons of the Bertibubba Supersuite that intruded the Errabiddy Shear Zone and the proto-Yarlarweelor Gneiss Complex (Fig. 8), were primarily derived from melting of Dalgaringa Supersuite rocks. The intrusion of these ca. 1960 Ma granites and similar ca. 1950 Ma granitic dykes into the southernmost Glenburgh Terrane marks the end of the Glenburgh Orogeny.

In the southern Capricorn Orogen, there is an absence of tectonism and magmatism between the 2000–1960 Ma Glenburgh Orogeny and the 1830–1780 Ma Capricorn Orogeny, which probably reflects changes in the tectonic setting of the region during this time. Unlike the Dalgaringa Supersuite, the 1965–1945 Ma Bertibubba Supersuite and Capricorn-aged granites intrude across the Glenburgh Terrane, Errabiddy Shear Zone, and the Yarlarweelor Gneiss Complex, confirming that the Glenburgh Terrane had accreted onto the Yilgarn Craton prior to the Capricorn Orogeny. Capricorn Orogeny granites consist of monzogranite, with some syenogranite and granodiorite, whereas the Dalgaringa Supersuite, of the Glenburgh Terrane, contains more intermediate compositions, more indicative of arc-type magmatism. However, the regional extent of the Glenburgh Terrane is still unknown. It may have collided and accreted onto the Pilbara Craton (Fig. 1) to form the Ophthalmia fold belt (a northward-verging fold belt exposed on the southern margin of the Pilbara Craton) which developed soon after ca. 2450 Ma (Martin et al., 2000), and then collided (together with the Pilbara Craton) with the Yilgarn Craton during the Glenburgh Orogeny.

5. Conclusions

Extensive regional mapping, and careful sampling for U–Pb SHRIMP geochronology, and geochemistry (Sheppard et al., 2004) in the southern Capricorn Orogen has led to a greater understanding of the region and to the recognition of the existence of the 2000–1960 Ma Glenburgh Orogeny. These results have allowed the tectonic framework and formation of the Glenburgh Terrane, Errabiddy Shear Zone, Yarlarweelor Gneiss Complex and Bryah–Padbury basins to be pieced together.

Previous models for the evolution of the Capricorn Orogen have not taken the Glenburgh Orogeny

into account, and only explain the evolution of the orogen in terms of a single Palaeoproterozoic orogenic event—the Capricorn Orogeny. In the light of these new data, these models must be revised. The 130 million year hiatus between the end of the Glenburgh Orogeny and the start of the Capricorn Orogeny in the southern Capricorn Orogen also needs to be explained.

Tectonic models for the Capricorn Orogeny, which in recent times has mainly been explained in terms of continent–continent collision (Tyler and Thorne, 1990; Myers et al., 1996; Pirajno et al., 1998) may also require revision. The lack of arc-type granitic rocks aged between 1960 and 1830 Ma suggests that the Capricorn Orogeny may have been the result of intracratonic processes (Gee, 1979). The presence of granites in the Glenburgh Terrane, which may have formed in an Andean-type setting (Sheppard et al., 1999) is consistent with the Glenburgh Terrane being accreted to the northern margin of the Yilgarn Craton during the Glenburgh Orogeny at c. 1960 Ma, possibly as part of a combined Pilbara–Glenburgh Craton.

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