A structural metamorphic study of the Broken Hill Block, NSW, Australia

C. J. Forbes, P. G. Betts, R. Weinberg, and I. S. Buick

ABSTRACT The prograde pressure–temperature ($P$–$T$) path for the complexly polydeformed Proterozoic Broken Hill Block (Australia) has been reconstructed through detailed structural analysis in conjunction with calculation of compositionally specific $P$–$T$ pseudosections of pelitic rock units within a high-temperature shear zone that formed early in the tectonic evolution of the terrane. Whilst the overall $P$–$T$ path for the Broken Hill Block has been interpreted to be anticlockwise, the prograde portion of this path has been unresolved. Our results have constrained part of this prograde path, showing an early heating event ($M_1$) at $P$–$T$ conditions of at least $c.$ 600 °C and 2.8–4.2 kbar, associated with an elevated geothermal gradient ($c.$ 41–61 °C km$^{-1}$). This event is interpreted to be the result of rifting at $c.$ 1.69–1.67 Ga, or at $c.$ 1.64–1.61 in the Broken Hill Block. Early rifting was followed by an episode of lithospheric thermal relaxation and burial, during which time sag-phase sediments of the upper Broken Hill stratigraphy (Paragon Group) were deposited. Following sedimentation, a second tectonothermal event ($M_2/D_2$) occurred. This event is associated with peak low-pressure granulite facies metamorphism ($c.$ 1.6 Ga) and attained conditions of at least 740 °C at 5 kbar. A regionally pervasive, high-temperature fabric ($S_2$) developed during the $M_2/D_2$ event, and deformation was accommodated along lithology-parallel, high-temperature shear zones. The larger-scale deformation regime (extensional or shortening) of this event remains unresolved. The $M_2/D_2$ event was terminated by intense crustal shortening during the Olarian Orogeny, during which time the first mappable folds within the Broken Hill Block developed.

Key words: Broken Hill Block; geothermal gradients; high-temperature shear zones; metamorphism; prograde $P$–$T$ path.

INTRODUCTION

Pressure–temperature ($P$–$T$) paths are extremely useful in determining the orogenic history of a region, and a well-constrained $P$–$T$ path will allow delineation of the relative timing of burial, heating, and uplift and exhumation of a terrane. Through recognition of clockwise or anticlockwise $P$–$T$ paths, characteristic $P$–$T$ evolutions of burial and heating (clockwise) or heating and burial (anticlockwise) followed by exhumation can be constructed. In many cases, absolute ages can be incorporated into the history so that pressure–temperature–time ($P$–$T$–$t$) paths can be constructed, placing even tighter constraint on the orogenic history (e.g. Kamber et al., 1998; Müller, 2003).

By combining the $P$–$T$–$t$ path with field observations, the $P$–$T$ evolution of a terrane can be combined with its deformation history. In this way, structures that may have accommodated bulk strain and/or deformation, or that may have influenced the large-scale geometry of a terrane may be more easily recognized and characterized, leading to the development of more complete geological histories and better constraints on the tectonothermal architecture of an orogen.

However, difficulties are often encountered within complexly polydeformed terranes where evidence of the early $P$–$T$ and deformational history has been obscured by episodic deformation and/or metamorphic events. In these cases, only partial construction of a $P$–$T$ path may be possible, and recognition of early deformation elements becomes difficult and often surrounded by controversy (e.g. Boger & White, 2003).

The Palaeoproterozoic Broken Hill Block, western New South Wales, Australia, is such a terrane where the prolonged and intense deformational and metamorphic evolution of the terrane has hindered reconstruction of its early history. The $P$–$T$ paths constructed for this terrane (e.g. Stüwe & Ehlers, 1997), although vital to partially establishing the terrane history, have focussed on the post-peak metamorphic history associated with the Olarian Orogeny ($c.$ 1.6–1.59 Ga; Page et al., 2000a), and the prograde path remains unconstrained. This paper focuses on understanding the relationships between deformation and metamorphism within an early-formed high-temperature shear zone in the southern Broken Hill Block,
with the aim of reconstructing the prograde $P$–$T$ path. Detailed structural analysis was conducted in conjunction with metamorphic petrology and calculation of $P$–$T$ pseudosections across the shear zone. Reconstruction of the prograde $P$–$T$ path allows resolution of previously unrecognized geothermal anomalies, which assist in modelling the early tectonothermal architecture of this complex region.

**THE BROKEN HILL BLOCK**

The Broken Hill Block (Fig. 1) comprises palaeoproterozoic metasediments intercalated with mafic and felsic intrusive and extrusive igneous rocks that are collectively termed the Willyama Supergroup (Fig. 2; Stevens et al., 1988). The sediments were deposited within an intraplate rift basin (Stevens et al., 1988) between c. 1.71–1.67 Ga (Page et al., 2000a). Sag-phase sediments of the upper Willyama Supergroup (Paragon Group, Fig. 2) were deposited between 1.66 and 1.6 Ga (Page et al., 2000a; Raetz et al., 2002). The Willyama Supergroup underwent intense shortening and metamorphism during the Olarian Orogeny c. 1.6–1.59 Ga (Page et al., 2000a). Early stages of orogenesis involved thin-skinned deformation and the development of large-scale recumbent (e.g. Marjoribanks et al., 1980; Hobbs et al., 1984) to shallowly inclined, highly non-cylindrical (sheath-like) folds (Forbes et al., 2004) associated with high-temperature, low-pressure amphibolite to granulite facies metamorphism.

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![Geological map of the Broken Hill Block showing the locality of the Round Hill Area (modified from Willis et al., 1983).](image-url)
Broken Hill Block has since been re-interpreted in the greenschist facies during the Delamerian Orogeny. Adelaidean sediments and Willyama Supergroup basement were then deformed and metamorphosed to high-grade amphibolite to granulite facies metamorphism in the southern Broken Hill Block, and greenschist facies metamorphism in the north (Binns, 1964; Phillips, 1980; Phillips & Wall, 1981). This interpretation has since been challenged by Stüwe & Ehlers (1997), who identified two distinct metamorphic events within the block. The first event occurred at 4–5 kbar and 650 °C, and is associated with early shortening at c. 1600 Ma. This event is termed M2 by Stüwe & Ehlers (1997), as it is suspected to have occurred post-peak metamorphism (M1). Their second metamorphic event (M3) was a garnet + chloritoid + staurolite + chloride mineral assemblage that formed at 5 kbar and 480 °C. This assemblage statically overprints a foliation that is associated with upright folding (Stüwe & Ehlers, 1997).

The timing of this static overprint is suggested to be as young as the Grenvillian (c. 1.1 Ga) or Pan-African (550–500 Ma) (Stüwe & Ehlers, 1997).

An opposing view was recently put forward by Swapp & Frost (2003), who suggested that the Broken Hill Block may have undergone higher-pressure metamorphism up to conditions above 9 kbar at 775 °C, based on the presence of rutile in equilibrium with garnet, aluminosilicate, and ilmenite in granulite facies pelites preserved in the Round Hill Area (Fig. 1).

Recently, Noble (2000); Venn (2001) and Gibson & Nutman (2004) have suggested that the earliest phases of deformation in the Broken Hill Block were the result of mid-crustal extension. This type of extensional model can account for regional high-temperature, low-pressure metamorphism and the development of a pervasive lithology-parallel fabric defined by a high-temperature, low-pressure mineral assemblage that is not associated with any folding in the area (e.g. Noble, 2000; Venn, 2001; Gibson & Nutman, 2004). However, the timing of lithospheric thinning is conjectural, and may be contemporaneous with basin evolution and deposition of the Willyama Supergroup c. 1.69 Ga (Gibson & Nutman, 2004), or may have occurred immediately prior to the Olarian Orogeny at c. 1.61 Ga (Venn, 2001).

**THE ROUND HILL AREA**

The Round Hill Area, located in the southern Broken Hill Block (Figs 1 & 3) has undergone multiple phases of deformation associated with amphibolite to granulite facies metamorphism, and preserves a well-exposed early high-temperature shear zone. The Round Hill Area has been subdivided in this study into the southern and northern areas (Fig. 3) based on differences in strain and degree of leucosome development. The Southern Round Hill Area is dominated by partially melted metasediments of the Thackaringa Group.
and middle to upper parts of the Broken Hill Group (Fig. 2) (Bradley, 1980). The Northern Round Hill Area comprises interbedded psammite and pelite units of the Sundown Group (Fig. 2) (Bradley, 1980).

Southern Round Hill Area

The Southern Round Hill Area (Fig. 3) comprises partially melted metasedimentary rocks that preserve well-defined quartzofeldspathic leucosome layers (Fig. 4a,b). Leucosomes are 8–10 cm wide and are commonly sub-parallel to compositional layering and the dominant, layer-parallel foliation preserved within the metasedimentary rocks. The leucosomes comprise medium- to coarse-grained (up to 5 mm) quartz + feldspar, and encompass garnet clusters that form small, disjointed and highly fractured clots that aggregate to form large (up to 5 cm diameter), irregular-shaped masses (Fig. 4a,b).

The host rock to the leucosomes is dominated by sillimanite-biotite-garnet pelitic gneiss interlayered with lesser psammopelitic to psammitic layers. Foliations are best developed within the pelitic layers. Two generations of sillimanite are preserved within the pelites. The first occurs as fibrolitic, milky white wisps up to 3 cm length, and are overprinted by coarse sillimanite prisms up to 5 cm length. Alkali feldspar is generally the only feldspar in the rock, and is commonly partially to totally retrogressed to sericite and fine-grained quartz. Garnet porphyroblasts are up to 7 cm in length, and are wrapped by the dominant foliation in the area (S2). The garnet often occurs as irregular-shaped clots, however, they occasionally show dextral, and more commonly, sinistral asymmetry.

Fig. 3. Geological map of the Round Hill Area showing the high-temperature shear zone mapped in this study. The Northern and Southern Round Hill Areas, and locality of selected samples used are shown.

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Psammopelitic to psammitic layers are up to 30 cm thick and are dominated by quartz and feldspar with minor biotite, sillimanite and subordinate fine-grained garnet. Foliations are not as well developed in these layers as in the pelitic layers. A well-developed quartz, sillimanite and biotite mineral lineation (Lm) is preserved on the plane of compositional layering. The mineral lineations plunge moderately W–SW throughout the area (Fig. 5).

Strain intensity gradually increases northwards through the Southern Round Hill area towards a high-temperature shear zone (Fig. 3) that separates the Southern from the Northern Round Hill Area. The high-temperature shear zone is defined by increased development of kinematic shear features such as S-C fabrics and sheared porphyroclasts. The C-fabric is NE-trending and mostly dips moderately to the NW (Fig. 3). Aspect ratios of garnet porphyroblasts increase from c. 1:1 in the south to c. 14:1 in the north of the area (Noble, 2000). Within the shear zone, the Lm mineral lineation becomes more pronounced on the S1 plane and the defining sillimanite, biotite and quartz minerals become more elongate. It is difficult to determine an overall shear sense on the high-temperature shear zone as it has most likely been reactivated at least once since its formation. The original orientation of the shear zone is also difficult to determine due to refolding during later events.

Small, retrograde shear zones up to c. 25 m wide anastamose through the northern extent of the Southern Round Hill Area (Fig. 3), and can easily be distinguished from the high-temperature shear zone as they are dominated by phyllicite, chlorite ± sericite-rich metasedimentary rocks that preserve a well-developed muscovite ± chlorite mineral lineation. The northern extent of the Southern Round Hill Area is defined by a marked decrease in kinematic indicators (S-C fabric, sheared porphyroblasts).

Northern Round Hill Area

The Northern Round Hill Area (Fig. 3) comprises pelite-dominated metasedimentary rocks interbedded with lesser psammite, which preserve less evidence of leucosome development or strain partitioning into high-temperature shear zones than in the Southern Round Hill Area (Fig. 4c). Pelitic units comprise sillimanite, biotite, quartz, feldspar (dominantly K-feldspar) and garnet. Garnet occurs as irregularly shaped clots up to 3 cm in length. However, these become less common and smaller in size towards the north of the Northern Round Hill Area. Sillimanite occurs as aligned, elongate, milky white needles up to 3 cm in length. Psammitic layers are up to 30 cm thick and comprise medium-grained quartz, feldspar (dominantly alkali feldspar), biotite and minor sillimanite. The Lm mineral lineation is not as well developed in the Northern Round Hill Area as in the Southern Round Hill Area; however, where preserved, it plunges moderately SW (Fig. 5a).

Numerous retrograde shear zones occur sub-parallel to compositional layering and S1 throughout the Northern Round Hill Area. These retrograde shear zones are defined by phyllicite metasediments preserving a well-developed muscovite ± chlorite lineation. Pegmatites comprising coarse grained quartz, feldspar and platy white mica are also preserved sub-parallel to compositional layering and S1 throughout the Northern Round Hill Area. The pegmatites are up to 20 m wide and are occasionally foliated by S3.

Deformation elements recognizable in the field

The earliest fabric recognizable in outcrop within the Round Hill Area is a pervasive, well-developed foliation that occurs parallel to compositional layering and is best developed within pelitic horizons. This fabric is termed S2 as it post-dates an inclusion fabric (S1) that is defined by alignment of fine-grained biotite and sillimanite, and has only been recognized in thin section. This assemblage is described in the petrogenesis section. S2 is defined by sillimanite and aligned aggregates of feldspar + quartz. Sillimanite occurs as fibrolitic wisps that anastamose between other grain aggregates within the Southern Round Hill Area. In the Northern Round Hill Area, sillimanite within the S2 fabric tends to be more prismatic. S2 wraps around garnet porphyroblasts and generally trends N–NE (020–045°), and is moderately to steeply dipping (Figs 3 & 5b); however, it becomes more variably oriented in the Northern Round Hill Area, where it has been folded during later deformation events (Figs 3 & 5b). No

Fig. 4. Field photographs of the Round Hill Area. Southern Round Hill Area pelites showing well-developed leucosomes (light layers) (a and b). Garnet clots in leucosome and mesosome layers (b). Lighter is c. 5 cm long. (c) Interbedded psammitic and pelite from the Northern Round Hill Area. Pencil is c. 15 cm length.
folding associated with S2 has been documented. Within the Southern Round Hill Area, the S2 fabric defines a shear fabric preserving moderate- to well-developed S-C fabrics.

The third-generation foliation (S3) is c. 1 mm spaced and defined by biotite and coarse-grained sillimanite prisms that cut through and overprint garnet porphyroblasts. S3 is commonly shallowly to moderately dipping, and variably oriented throughout the area (Fig. 5c). The S3 fabric trend is often at a high-angle (60–90°) to S2 (Fig. 3). Within the Northern Round Hill Area, S3 is axial planar to inclined to recumbent, tight to open folds. F3 folds are variably plunging because of later refolding (Fig. 5d). Recumbent F3 folds have been interpreted as regional F2 folds by Forbes & Betts (2004) and Forbes et al. (2004), and as F1 folds by Marjoribanks et al. (1980) and Hobbs et al. (1984).

The fourth-generation fabric (S4) is a well developed, c. 2–5 mm spaced foliation defined by sillimanite and lesser biotite that overgrows and crenulates pre-existing fabrics. S4 trends NE (020–030°), is steeply dipping (Fig. 5e), and is commonly sub-parallel or at a low angle to S2. Within the Northern Round Hill Area, S4 is also defined by spaced (up to 2 cm) stylolites and fractures (up to 10 cm spacing). Within the Northern Round Hill Area, S4 is axial planar to upright, open to close, parallel folds that are mostly plunging shallowly to the SW, however occasionally plunge steeply to the NW (Fig. 5f). This may be attributed to gentle warping during later deformation.

**METAMORPHIC PETROLOGY**

**Petrogenesis**

The petrogenesis of pelites from the Southern and Northern Round Hill Areas was determined from thin-section analysis. In general, a similar sequence of overprinting minerals was observed, with subtle but significant differences in samples from the different areas. This section presents these mineral overprinting relationships, followed by an interpretation of the mineral petrogenesis and its relation to mapped structural elements.

**Observed mineral overprinting relationships**

The earliest recognized mineral assemblage is represented by fine-grained biotite + quartz + sillimanite ± plagioclase ± muscovite inclusions preserved within coarse-grained minerals that comprise the

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Fig. 5. Equal-area stereographic projections presenting data from the Round Hill Area. (a) Mineral lineations defined by sillimanite + biotite + quartz; (b) Poles to S2; (c) Poles to S3; (d) L3 intersections (solid squares and circles); F3 plunge-plunge directions (open squares); (e) Poles to S4; (f) L4 intersections.
matrix of the pelites. Biotite, quartz and sillimanite inclusions occur within K-feldspar and retrogressed cordierite porphyroblasts (Fig. 6a,b). Biotite has a deep red colour, and appears as euhedral, tabular grains that are commonly equally spaced and aligned (Fig. 6a–c); however, locally it can show a more random orientation. Quartz inclusions occur as small, round grains, and the less common sillimanite inclusions occur as fine, prismatic grains that are often aligned in a similar orientation to biotite inclusions. Within the shear zone (sample RHA51; Fig. 3), rare fine-grained inclusions of plagioclase occur within cordierite porphyroblasts. Muscovite also occurs within the cordierite inclusions as semi-continuous grains with highly irregular grain boundaries as the result of chlorite and sericite (pinite) retrogression of the hosting cordierite. The muscovite also has higher birefringence than the surrounding pinitized cordierite.

Inclusions of sillimanite and, less commonly, biotite are also observed within garnet porphyroblasts (Fig. 6d). Sillimanite inclusions are fine-grained needles and are locally randomly oriented, but generally have an overall trend through the garnet that locally has a sigmoidal shape, possibly as the result of shearing associated with later fabric development. Where observed, biotite inclusions within garnet are euhedral to subhedral, and occasionally contain sillimanite inclusions that are continuous into the host garnet.

Small plagioclase feldspar and biotite grains, interpreted to be related to the inclusion assemblage, also occasionally occur within the matrix. Biotite has highly irregular grain boundaries and a deep red-brown colour. Plagioclase feldspar is commonly sericitized, has highly irregular grain boundaries, and is highly fractured (Fig. 6e).

The matrix of the pelites comprises granoblastic garnet, cordierite, quartz, feldspar and biotite (Fig. 6f). Cordierite is retrogressed to pinite (chlorite + sericite), and contains remnant, black radiation haloes attributed to monazite and zircon inclusions. Large feldspar grains are orthoclase-rich alkali feldspar (see Mineral chemistry) with very fine exsolution lamellae occasionally observed. In general, the K-feldspar does not display twinning, and is easily distinguished from matrix quartz by its poikioblastic texture. Partial to total retrogression of K-feldspar to sericite and fine-grained quartz is evident. Matrix quartz is commonly recrystallized and inclusion-free. Biotite interpreted to be part of the granoblastic matrix assemblage commonly occurs at the grain boundaries of quartz, K-feldspar and cordierite, or as small, decussate aggregates (Fig. 6f). The biotite has a euhedral to subhedral habit, and is of paler colour than the biotite in the inclusion assemblage, commonly having a brown colour in plane-polarized light. The biotite is also observed partially within cordierite, where it occasionally contains fine-grained sillimanite and small, round quartz inclusions. Grain boundaries of biotite within cordierite are commonly irregular and diffuse, possibly as the result of retrogression of cordierite.

Garnet occurs as large porphyroblasts that commonly display an elongate shape; however, in the Northern Round Hill Area, garnet tends to be more rounded in shape. Garnet can be classified into two types; inclusion-poor and -rich, the latter being not common north of the high-temperature shear zone. Inclusion-poor garnet (Fig. 6a,c) commonly has well-defined grain boundaries and contains globular-shaped inclusions of quartz and possibly feldspar; however, the feldspar is retrogressed and difficult to identify. The garnet itself is relatively clear. Inclusion-rich garnet is characterized by the high density of included sillimanite (Fig. 6a,c). However, this type of garnet lacks the globular quartz and feldspar inclusions observed within the inclusion-poor garnet (Fig. 6b,d). The sillimanite inclusions are continuous outside the garnet and into the matrix, where sillimanite appears as randomly oriented fibrolitic mats.

The granoblastic matrix is preserved as lensoidal pods that are wrapped by the dominant fabric within the pelites. In the Southern Round Hill Area, fibrolitic mats define the fabric. Pseudomorphed porphyroblasts, possibly once andalusite, occasionally occur within the fabric (Fig. 6g). However, definite identification of the primary mineral remains uncertain as the porphyroblasts are uncommon, they are small in size and have been highly deformed during simple shearing. S-C foliations are preserved within the dominant fabric. In the Northern Round Hill Area, a mix of fibrolite and prismatic sillimanite, which are fractured and broken because of later deformation, define the fabric. Evidence of shearing within the fabric is not as prominent. In all samples, the fabric cross-cuts the granoblastic matrix; however, locally garnet porphyroblasts show evidence of being dragged into the fabric, resulting in a slight sigmoidal shape. In thin section, sillimanite inclusions within the garnet are also dragged into the main fabric, occasionally giving an ‘S’-shape to the overall sillimanite inclusion fabric trend. Microlithons of earlier grown red-brown and pale brown coloured biotite occur within the fabric, and are particularly common in samples in the Southern Round Hill Area. The grain boundaries of the biotite are highly irregular where they are in contact with the main fabric.

Sprays of fine sillimanite needles oriented sub-parallel to the trend of the dominant fabric are focussed along grain boundaries and overprint minerals within the coarse-grained matrix, particularly K-feldspar, cordierite and quartz (Fig. 6f). Late retrograde biotite locally overgrows the garnet porphyroblasts. The biotite preserves sillimanite inclusions (where present within pre-existing garnet), and has an anhedral shape that mimics the grain boundaries of the garnet. Coarse-grained, euhedral sillimanite prisms cross-cut all pre-existing mineral assemblages (Fig. 6c). The sillimanite prisms either occur with their c-axis both sub-parallel and orthogonal to the thin section surface.
Fig. 6. Photomicrographs from the Round Hill Area. (a) S1 inclusion fabric defined by fine-grained biotite preserved within K-feldspar (ksp) grains. The fabric has a similar orientation in multiple K-feldspar grains within the photo. The S2 fabric is defined by fibrolite (RHA51); (b) S1 inclusion fabric defined by fine-grained biotite (bi) preserved within K-feldspar (ksp). The S2 fabric cross cuts the coarse K-feldspar and garnet (g) within the photograph. Inclusion-rich (top) and -poor (bottom) garnet can be seen in the photograph (RHA51); (c) rare S1 inclusion fabric defined by biotite from sample RHA58. Late coarse-grained sillimanite (S3) overprints the coarse-grained matrix assemblages and S2; (d) inclusion-rich garnet (g with sill) hosting fine sillimanite needles, and inclusion-poor garnet (g) (RHA59); (e) rare plagioclase (pl) preserved within cordierite (cd) (RHA59); (f) Example of coarse-grained matrix of the pelites comprising cordierite (cd), K-feldspar (ksp) and quartz (qtz). Fine-grained biotite inclusions define the S1 fabric; (g) sheared porphyroblasts pseudomorphed by fibrolite within the S2 fabric. The oxide in the photograph is ilmenite (ilm).
The most obvious difference between the mineral petrogenesis of the Southern and Northern Round Hill Areas is the development of the inclusion assemblage, which is very commonly preserved within the Southern Round Hill Area but is much less common in the Northern Round Hill Area. Where observed in the Northern Round Hill Area, the inclusions are defined solely by biotite (Fig. 6c). Plagioclase was not observed in the matrix of the sample from the Northern Round Hill Area. Garnet porphyroblasts within the Northern Round Hill area also lack the numerous sillimanite and occasional biotite inclusions that are common within garnet in the Southern Round Hill Area (Fig. 6d). Within the Northern Round Hill Area, rare partial rims of younger garnet growth are observed. The late garnet has partly euhedral grain boundaries and overgrows the dominant fabric. As this garnet growth occurred after the earliest stages of orogenesis, which is the focus of this study, the origin of the partial rims is not further considered.

Interpreted mineral petrogenesis

The aligned inclusion assemblage represents the earliest phase of recognizable mineral growth in the Round Hill pelites, and defines S1. It shows a general pattern of segregation into sillimanite-rich zones within garnet porphyroblasts, and biotite + sillimanite ± plagioclase ± muscovite-rich zones outside of garnet porphyroblasts within cordierite and K-feldspar. This may be a function of compositional differences in the original sediment, or may be the result of local strain variations within the rock at the time the metamorphic minerals defining the inclusion assemblage were growing. In the latter case, sillimanite-rich zones are representative of locally high-strain domains (e.g. Cobbold, 1977; Bell & Rubenach, 1983; Vernon, 1996). Additionally, the S1 fabric may be associated with larger-scale strain variation as it is better developed within higher-strain areas of the Southern Round Hill Area. However, relating this potential strain partitioning to a tectonic event is highly ambiguous as the fabric has only been recognized as an inclusion assemblage in thin section.

The granoblastic minerals overgrowing the inclusion assemblage are generally separated into garnet-rich zones and K-feldspar + cordierite + quartz-rich zones. This is interpreted to be due to the ease of mineral nucleation and growth within different parts of a pre-existing, partially developed fabric. The remnants of the pre-existing fabric are represented by the inclusions described as the earliest recognizable mineral assemblage. During prograde metamorphism, K-feldspar and cordierite would have preferentially grown within original quartz- and feldspar-rich zones, and garnet nucleation would have been preferable in zones rich in sillimanite and biotite (e.g. Daniel & Spear, 1998) (Fig. 7). Overall, the textural relationships between coarse matrix minerals and the occurrence of leucosomes suggest that the following reaction (e.g. Yardley, 1989) has occurred:

\[
\text{biotite} + \text{sillimanite} + \text{plagioclase} + \text{quartz} = \text{cordierite} + \text{garnet} + \text{K-feldspar} + \text{liquid.}
\]

Nucleation and rapid growth of multiple garnet resulted in them eventually coalescing to form large porphyroblasts (Fig. 7). The original garnet nuclei have become unrecognizable because of compositional homogenization of the garnet at high temperatures, which would erase any compositional gradients developed during the original growth (Daniel & Spear, 1998). Garnet that is free of sillimanite inclusions is interpreted to have overgrown pods of originally quartz and feldspar-rich material that occurred within the sillimanite + biotite rich zones of the original fabric (Fig. 7). Therefore, although there appear to be two texturally different types of garnet within the peak assemblage, they are interpreted to be of the same generation.

The dominant (fibrolitic) sillimanite fabric described in the thin sections is the mapped S2 fabric. The microstructural relationship of the S2 fabric wrapping and truncating the granoblastic garnet + cordierite + K-feldspar + quartz mineral assemblage can be used to interpret the relative timing of growth of the two mineral assemblages in two ways: (1) as two separate metamorphic events where the garnet + cordierite + K-feldspar + quartz assemblage grew during an early event and was overprinted by a second event associated with growth of the dominant fabric and also synchronous with deformation (e.g. Hand et al., 1992); or (2) a single event whereby the coarse-grained mineral assemblage grew in locally low-strain domains within the rock unit, and the fibrolitic sillimanite foliation grew within high-strain domains (e.g. Vernon, 1987, 1996).

Distinguishing between these two scenarios for the Round Hill pelites is difficult, but may be done if one mineral assemblage is recognized as being unstable during the growth of the other (see Vernon, 1996). However, the minerals of the two assemblages within the Round Hill pelites (cordierite + garnet + K-feldspar + quartz and fibrolitic sillimanite) are stable with one another (see following section on pseudosections) at granulite facies conditions.

Careful geochronological analysis of datable minerals (e.g. zircon, monazite) that can be demonstrated to have grown synchronously with the metamorphic mineral assemblages may be used to distinguish between the scenarios (see Vernon, 1996); however, no such isotopic data are available. Previous dating of the timing of peak metamorphism (c. 1.6 Ga; Page & Laing, 1992) and the Olarian Orogeny (c. 1.6–1.59 Ga; Page et al., 2000a) may be useful for constraining the relative timing of growth of the peak mineral assemblage and the S2 fabric. The coarse-grained, blocky sillimanite prisms that overprint the
Fig. 7. Schematic sketch of the interpreted mineral petrogenesis for the Round Hill pelites (see text for explanation); Bi, biotite; cd, cordierite; fsp, feldspar; g, garnet; ksp, K-feldspar; mu, muscovite; pl, plagioclase; q, quartz; sill, sillimanite.
high-temperature mineral assemblage (Fig. 6e) are interpreted to define the S3 fabric that is axial planar to the first generation of folds mapped in the Round Hill Area, and are considered to have developed during the earliest stages of the Olarian Orogeny following peak metamorphism (Page & Laing, 1992; Page et al., 2000a). The combination of overprinting relationships and published ages of peak metamorphism and timing of the Olarian Orogeny implies the S2 fabric must have developed almost synchronously with the peak mineral assemblage. The close temporal relationship between the peak assemblage and the S2 fabric implies the coarse grained garnet + cordierite + K-feldspar + quartz peak assemblage may have grown in locally low-strain domains, and the fibrolitic sillimanite foliation within locally high-strain domains during a single granulite facies metamorphic event. Localized strain contrasts within the pelites developed during deformation, and different metamorphic minerals preferentially nucleated and grew within the high and low strain zones. The splays of fine sillimanite needles oriented sub-parallel to the trend of the dominant fabric and overprinting the coarse-grained assemblage within the low-strain zones are interpreted to have grown with the S2 fabric. This synchronous growth of sillimanite in both high- and low-strain zones was also described by Vernon (1996).

### Table 1. Representative electron microprobe mineral analyses for sample RHA59, representing pelitic rocks below the high-temperature shear zone.

<table>
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**Sample RHA59R**

### Mineral chemistry

Electron microprobe analyses were undertaken on four thin sections of metapelite, one each from samples RHA58 and RHA59, and two from sample RHA51 (Fig. 3) to determine the compositions of minerals and identify any zoning. Analyses were conducted using a Cameca SX50 electron microprobe at the University of Melbourne Joint Electron Microprobe (JEM) Facility, using an accelerating voltage of 15 kV, and a current of 25.05 μA. PAP matrix corrections were used for matrix correction and data reduction. Representative results for individual samples are shown in Tables 1–3. The Fe³⁺ content in garnet, feldspar, biotite, sericite and ilmenite was estimated using the AX software of Holland and Powell (http://www.esc.cam.ac.uk/astaff/holland/ax.html).

### Garnet

Garnet porphyroblasts were analysed in sections RHA59R, RHA51A and RHA51B. In all cases, garnet is almandine-rich (average X₉₃, sample RHA59 = 0.82; sample RHA51 = 0.81), with minor pyrope, and negligible grossular and spessartine contents (Tables 1 & 2; Fig. 8). Garnet profiles mostly show localized variations in composition, with no obvious zonation patterns (Tables 1 & 2; Fig. 8), possibly reflecting homogenization of garnet because of intragranular diffusion during high-temperature metamorphism (e.g. Bohlen, 1987; Marmo et al., 2002). However, localized rimward increases in almandine content and a corresponding decrease in pyrope content were observed in sample RHA59 (Fig. 8b), and weakly within both thin sections from sample RHA51 (e.g. Fig. 8d). This is interpreted to reflect minor diffusional Fe-Mg exchange during cooling. Minor to negligible variation in grossular and spessartine contents occur in these profiles.
Table 2. Representative electron microprobe mineral analyses for sample RHA51, representing pelitic rocks within the high-temperature shear zone.

<table>
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<th>Mineral:</th>
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<th>gnt (rim)</th>
<th>gnt (core)</th>
<th>gnt (rim)</th>
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<th>fsp</th>
<th>fsp</th>
<th>fsp</th>
<th>bi (incl.)</th>
<th>bi (incl.)</th>
<th>bi (early)</th>
<th>bi (after gnt)</th>
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<td>100.72</td>
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<td>96.03</td>
<td>100.74</td>
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</table>

Sample locality is shown in Fig. 3.

Table 3. Representative electron microprobe mineral analyses for sample RHA58, representing pelitic rocks above the high-temperature shear zone.

| Mineral: | fsp | fsp | fsp | fsp | bi (incl.) | bi (early) | bi (clear) | bi (hydro) | sill (fol.) | sill (fol.) | sill (blade) | ser | ser | ser | ilm | ilm |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| SiO2 | 65.51 | 66.66 | 64.63 | 65.93 | 35.79 | 35.09 | 34.35 | 35.08 | 36.81 | 36.87 | 36.77 | 74.20 | 48.20 | 47.59 | 0.00 | 0.00 | 0.00 |
| TiO2 | 0.05 | 0.00 | 0.03 | 0.00 | 2.14 | 2.79 | 2.61 | 2.64 | 2.73 | 2.70 | 2.69 | 2.74 | 2.74 | 1.28 | 1.24 | 1.19 |
| Al2O3 | 18.73 | 19.54 | 18.84 | 19.14 | 19.32 | 19.88 | 19.24 | 19.01 | 63.06 | 63.16 | 62.99 | 35.75 | 36.53 | 35.62 | 0.00 | 0.00 | 0.02 |
| Cr2O3 | 0.00 | 0.01 | 0.01 | 0.00 | 0.02 | 0.02 | 0.03 | 0.03 | 0.05 | 0.11 | 0.08 | 0.01 | 0.01 | 0.00 | 0.00 | 0.05 |
| FeO | 0.01 | 0.01 | 0.04 | 0.00 | 21.12 | 22.01 | 22.37 | 21.48 | 0.08 | 0.08 | 0.15 | 1.18 | 1.10 | 1.19 | 45.77 | 45.57 | 45.55 |
| MnO | 0.01 | 0.00 | 0.01 | 0.02 | 0.07 | 0.02 | 0.06 | 0.08 | 0.01 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.22 | 0.79 | 0.75 |
| MgO | 0.00 | 0.00 | 0.01 | 0.00 | 7.35 | 7.23 | 7.39 | 7.46 | 0.02 | 0.00 | 0.02 | 0.74 | 0.71 | 0.78 | 0.09 | 0.11 | 0.11 |
| ZnO | 0.05 | 0.08 | 0.00 | 0.00 | 0.15 | 0.06 | 0.08 | 0.02 | 0.00 | 0.07 | 0.00 | 0.00 | 0.00 | 0.03 | 0.33 | 0.00 | 0.00 |
| CaO | 0.05 | 0.16 | 0.08 | 0.16 | 0.03 | 0.00 | 0.02 | 0.02 | 0.01 | 0.01 | 0.03 | 0.49 | 0.49 | 0.44 | 0.03 | 0.01 | 0.00 |
| Na2O | 1.83 | 6.15 | 3.00 | 3.50 | 0.10 | 0.07 | 0.12 | 0.12 | 0.12 | 0.02 | 0.01 | 0.00 | 0.49 | 0.49 | 0.44 | 0.03 | 0.01 |
| K2O | 13.90 | 8.15 | 12.23 | 11.77 | 8.33 | 9.10 | 9.07 | 9.07 | 0.01 | 0.00 | 0.00 | 10.55 | 10.54 | 10.62 | 0.00 | 0.00 | 0.00 |
| Total | 100.15 | 100.77 | 98.88 | 100.53 | 95.10 | 95.39 | 95.33 | 95.01 | 100.09 | 100.32 | 100.08 | 96.10 | 97.66 | 96.51 | 99.77 | 98.89 | 0.00 |

Sample locality is shown in Fig. 3.
Feldspar

Feldspar defining the peak metamorphic mineral assemblage was analysed in all four samples, and has high orthoclase content (Tables 1–3; Fig. 9). Alkali feldspar in sample RHA59R is dominantly orthoclase (Or$_{0.79-0.87}$), with minor albite (Ab$_{0.14-0.21}$) and no anorthite (An$_0$), where Or = K/(K + Na + Ca), Ab = Na/(K + Na + Ca) and An = Ca/(K + Na + Ca). Sample RHA51 is dominantly orthoclase (Or$_{0.74-0.86}$), with minor albite (Ab$_{0.14-0.26}$) and negligible anorthite (An$_{0.002-0.005}$). Sample RHA58L shows the highest variation in alkali feldspar composition of Or$_{46-83}$, Ab$_{17-53}$An$_{0.2-0.8}$ (Fig. 9). Plagioclase feldspar was not analysed as it is extensively sericitized, and where preserved is very fine-grained and highly fractured.

Biotite

Three generations of biotite were observed within the Round Hill Area. The earliest biotite occurs as fine-grained inclusions within cordierite and feldspar. Biotite inclusions throughout all samples have similar $X_{Fe}$ (Fe$^{2+}$/(Fe$^{2+}$ + Mg)), but are slightly more magnesian in sample RHA59R (RHA59R: $X_{Fe} = 0.60-0.62$; RHA51: $X_{Fe} = 0.61-0.62$; RHA58: $X_{Fe} = 0.61-0.62$). Biotite replacing garnet has a lower $X_{Fe}$ than the earlier biotite inclusions (RHA59R: $X_{Fe} = 0.57$; RHA51: $X_{Fe} = 0.55-0.58$). The average Ti content of biotite decreases from south to north (RHA59: Ti = 0.17–0.20 cations per 11 oxygen; RHA51: Ti = 0.18–0.19 cations pfu; RHA58: Ti = 0.12–0.19 cations pfu). The concentration of Ti within individual biotite generations did not show any consistent variation.

Sillimanite/fibrolite

Fibrolite was analysed from within the pervasive foliation preserved in the samples (Tables 1–3). The prisms cross-cutting the pervasive fabric and garnet porphyroblasts were determined to be sillimanite (Tables 1–3).

Oxides

All oxides analysed in the Round Hill Area are ilmenite (Tables 1–3). Ilmenite in sample RHA59R shows the highest variation, with $X_{Ilm}$ (Fe$^{2+}$/(Fe$^{2+}$ + Mn + Mg)) ranging from 0.97 to 0.98; $X_{Geik}$ (Mg/(Fe$^{2+}$ + Mn + Mg)) ranging from 0.004 to 0.0023 and $X_{Pyro}$ (Mn/(Fe$^{2+}$ + Mn + Mg)) ranging from 0.003 to 0.010. Sample RHA58L showed lesser variation in oxide composition ($X_{Ilm} = 0.98$; $X_{Geik} = 0.003–0.008$; $X_{Pyro} = 0.01–0.02$).

Cordierite

No unaltered cordierite was recognized in any samples.

Fig. 8. Compositional profiles through garnet. Sample localities shown in Fig. 3.

Fig. 9. Normalized orthoclase (Or):albite (Ab):anorthite (An) tri-plot for felspar analysed in the Round Hill pelites. Sample localities shown in Fig. 3.
P-T pseudosections

Pseudosections assist in visualization of changes in multivariant mineral assemblages and univariant reactions for a set bulk-rock composition over a range of P-T conditions (e.g. Hensen, 1971; Guiraud et al., 1990; Powell & Downes, 1990; White et al., 2001; Boger & White, 2003), and were used in this study to model the prograde P-T path of the Round Hill pelites. The pseudosections shown were calculated using the individual bulk-rock compositions of selected samples from across the Round Hill Area, which were analysed using the Geochemical Evolution and Metallogeny of Continents (GEMOC) XRF facilities at Macquarie University. Results of whole-rock XRF analysis are shown in Table 4. Three samples from across the Round Hill Area were selected for metamorphic analysis. Pseudosections were calculated in the model system Na2O-CaO-K2O-FeO-MgO-Al2O3-SiO2-H2O (NCKFMASH) using THERMOCALC (Powell & Holland, 1988; Powell et al., 1998). Pelites from the Southern Round Hill Area are represented by pseudosections drawn for samples RHA59 (Fig. 10a) and RHA51 (Fig. 10b). RHA51 was taken from within the high-strain zone of the Southern Round Hill Area. Figure 10(c) is taken to represent pelites in the Northern Round Hill Area, and is drawn for sample RHA58. Sample localities are shown in Fig. 3. Each section includes the phases andalusite (and), biotite (bi), chlorite (chl), clinzoisite (cz), cordierite (cd), garnet (g), K-feldspar (ksp), kyanite (ky), liquid (liq), muscovite (mu), plagioclase (pl), sillimanite (sill), and staurolite (st). Quartz (qtz) is assumed to be in excess throughout the whole system. H2O is assumed to be the pure fluid phase and in excess below the solidus. H2O was set individually for each section at the wet solidus so that the rocks were just fluid-saturated (Fig. 10a–c).

Setting the effective bulk-rock composition used to calculate a pseudosection is a highly critical step as this directly influences the series of metamorphic reactions seen within a rock. Mineral zonation within coarse-grained assemblages, particularly garnet, during prograde and retrograde events can significantly change the effective bulk-rock composition as mineral cores may become chemically isolated from the remainder of the rock during metamorphism (Stüwe, 1997; Marmo et al., 2002). Anhydrous minerals, such as garnet, commonly preserve extensive zonation resulting from slow diffusional processes during prograde metamorphism (e.g. Yardley, 1977; Vance & Holland, 1993; Clarke et al., 1997). However, at higher temperatures (e. >650 °C) the rate of volume diffusion increases and garnet can become chemically homogenized, limiting the extent of chemical fractionation of the bulk-rock composition (e.g. Woodsworth, 1977; Bohlen, 1987; Marmo et al., 2002). Electron microprobe results of the Round Hill samples show no significant chemical zonation within the minerals, particularly with respect to garnet (Fig. 8). As it would be difficult to account for any potential fractionation of the bulk-rock composition during porphyroblasts growth, we have assumed the analysed bulk-rock composition is a representative of the samples.

There is also the issue of a generally limited understanding of the original bulk composition of a rock prior to granulate facies metamorphism, and that the composition prior to peak metamorphism (i.e. during prograde metamorphism) would differ from that analysed now due to melt loss or gain during heating. This problem is manifest by the lack of knowledge of the volume of melt lost from or accumulated into the rock, the composition of this melt, and the awareness that the composition of the melt can change progressively throughout the history of the rock, also changing the bulk-rock composition (e.g. White & Powell, 2002). White et al. (2004) have described complex melt production within the Round Hill pelites, whereby production of melt was spatially focused around garnet nuclei. In this model, it is possible that a significant volume of melt may have migrated away from the site of melt production (White et al., 2004).

| Table 4. Normalized bulk-rock compositions (in wt%) for pelitic samples from the Round Hill Area (this study), and from across the Broken Hill Block (data taken from the Broken Hill GIS database compiled by the New South Wales Geological Survey). |
|------------------|------------------|------------------|------------------|------------------|------------------|------------------|------------------|------------------|------------------|
| Sample           | SiO2             | TiO2             | Al2O3            | Fe2O3            | MnO              | MgO              | CaO              | Na2O             | K2O              | P2O5             |
| RHA59            | 75.41            | 0.72             | 12.58            | 4.99             | 0.05             | 1.05             | 0.31             | 0.80             | 3.94             | 0.15             |
| RHA51            | 60.45            | 0.87             | 24.45            | 5.41             | 0.03             | 1.67             | 0.12             | 0.92             | 6.00             | 0.08             |
| RHA55            | 58.29            | 0.86             | 24.56            | 7.88             | 0.13             | 1.52             | 0.12             | 0.42             | 6.05             | 0.14             |
| RHA58            | 58.61            | 1.06             | 25.96            | 6.74             | 0.05             | 1.67             | 0.10             | 0.53             | 5.20             | 0.07             |
| RHA59            | 55.19            | 0.78             | 21.18            | 17.79            | 0.33             | 1.90             | 0.58             | 0.46             | 3.67             | 0.14             |
| Average all BHG & TG pelites | 61.56          | 0.91             | 21.03            | 8.47             | 0.21             | 1.69             | 0.83             | 0.63             | 4.55             | 0.12             |
| Average northern BHG & TG pelites | 60.49          | 0.98             | 22.25            | 8.19             | 0.11             | 1.68             | 0.42             | 0.78             | 4.98             | 0.11             |
| Average all SG pelites | 60.71          | 0.91             | 22.29            | 8.16             | 0.17             | 1.65             | 0.58             | 0.55             | 4.86             | 0.12             |
| Average northern SG pelites | 60.04          | 0.89             | 23.32            | 8.04             | 0.14             | 1.49             | 0.25             | 0.37             | 5.29             | 0.18             |

Data for samples RHA59, RHA51 and RHA58 was used to calculate pseudosections shown in Fig. 10a, b and c respectively. Sample localities are shown in Fig. 3. Average pelite compositions from across the Broken Hill Block taken for samples with SiO2 = 55–65 wt% and Na2O < 3 wt%.

TG, Thackaringa Group; BHG, Broken Hill Group; SG, Sundown Group.

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The whole-rock geochemistry of the Round Hill pelites used here have been compared with the whole-rock chemistry of stratigraphically equivalent units in lower grade (amphibolite facies) areas of the Broken Hill Block that have not undergone significant melting (Table 4; Fig. 11). Figure 11 shows that there is little significant difference between the compositions of amphibolite facies and partially melted granulite facies pelites, apart from sample RHA59, which is slightly more Fe-rich and Al-depleted (Fig. 11). As
the main phases formed through melting reaction (i.e. garnet and cordierite) have relatively low SiO₂ content, melt extraction should leave a restite with low Si, and high Mg, Fe, Al contents compared with normal pelite (e.g. Mengel et al., 2001; White & Powell, 2002). Table 4 shows the SiO₂ content of sample RHA59 is less than that of other Round Hill pelites and the average Broken Hill Group/Thackaringa Group and Sundown Group pelites, and that the Fe₂O₃ and MgO content of RHA59 is higher. This suggests sample RHA59 may be slightly restitic and may have lost some melt.

As sample RHA59 has the most restitic composition, it was used to calculate a trial pseudosection to test the sensitivity of the pseudosection to the addition of 30% melt of a given composition to the analysed bulk-rock composition (Fig. 12). The volume of melt added was chosen from the percentage of melt expected for an average pelitic composition at the approximate conditions of the Round Hill pelites, as calculated in the NCKFMASH system by White et al. (2001) (see also White & Powell, 2002). Field evidence shows that melt has been retained within the Round Hill pelites in the form of leucosomes (Fig. 4a,b), therefore the addition of 30% melt back into the pseudosection will model the largest possible variation in bulk-rock chemistry because of loss of melt from the system. The melt composition used to test the pseudosections was taken from White et al. (2001). The pseudosection topologies were very similar, and no significant variation in the position or slope of the wet solidus and the muscovite and biotite breakdown reactions are apparent (Figs 10a & 12).

As the only assumption used in the original pseudosections calculated for this study is the addition of H₂O to the point where the rocks were just saturated at the
wet solidus, and as the determination of the true composition and volume of melt lost from the Round Hill metapelites is beyond the scope of this study, we have assumed that the bulk-rock compositions determined using XRF analysis are the closest estimate there is to the effective bulk-rock composition of the Round Hill pelites. The following description of P–T paths determined for the Round Hill pelites is based on the original pseudosections calculated without attempting to add melt back into the bulk-rock composition.

**P–T paths**

This study focuses on the prograde P–T path of the pelites. Two metamorphic events were identified in the Round Hill Area. The first event (M1) is defined by the S1 inclusion assemblage and was synchronous with the D1 event. The second metamorphic event (M2) is represented by the coarse-grained peak mineral assemblage, and is considered to have been approximately synchronous with D2 deformation.

**M1**

The M1 event is characterized by the S1 mineral assemblage of biotite + sillimanite + plagioclase ± muscovite. This assemblage is stable over a wide field in P–T space, particularly for samples RHA51 (Fig. 10b) and RHA58 (Fig. 10c). The conditions of M1 metamorphism are best constrained using sample RHA59, for which the garnet stability field is large (Fig. 10a). The lack of garnet within the M1 assemblage places a pressure constraint on the conditions of metamorphism. M1 metamorphism therefore occurred at temperatures of at least c. 600 °C at pressure of c. 2.8–4.2 kbar (Fig. 10a).
The M2 event is represented by the coarse-grained garnet + cordierite + K-feldspar + sillimanite + quartz peak mineral assemblage identified in all samples, constraining peak metamorphic conditions to a single quadrivariant field in each pseudosection (Fig. 10a–c). For sample RHA59, this constrains M2 to between 4.5 and 6.5 kbar and 750 and 870 °C (Fig. 10a); to 5 to >8 kbar at greater than c. 750 °C within sample RHA51 (Fig. 10b); and to c. 4.8–8.1 kbar and 740 to greater than 900 °C in sample RHA58 (Fig. 10c). Overall, the fields in which the M2 assemblage within the Round Hill pelites fall indicate that high-grade conditions within the area attained pressures of at least c. 5 kbar and temperatures of at least 740 °C. These values agree with previous peak metamorphic estimates of Powell & Downes (1990), who reported conditions of 750–800 °C at c. 5 kbar for rocks in the Round Hill Area.

Overall P–T path

Two end-member prograde P–T paths from the M1/D1 to M2/D2 events have been drawn on Fig. 13. This path shows an increase in temperature of at least 140 °C associated with a pressure increase of c. 0.8–2.2 kbar, depending on the original pressure of the M1/D1 event (Fig. 13). This implies some burial between the D1 and D2 events.

It is noteworthy that if the petrogenesis of sample RHA59 is used on the trial pseudosection to which 30% melt was added (Fig. 12), no significant variation in the gradient of the P–T paths of the applied and trial pseudosections is apparent. This is considered supportive of using the applied pseudosection to determine the general prograde P–T path followed by the Round Hill pelites. However, extreme care would need to be taken in delineation of a detailed P–T path for these pelites (see Vernon, 1996), particularly in relation to addressing the issue of a changing bulk-rock composition during prograde metamorphism as a result of melt production and removal (see White & Powell, 2002).

The P–T path of the Round Hill Area can be further extended using the work of Stüwe & Ehlers (1997), who constructed a retrograde P–T path for the Nine Mile Area (Fig. 1), which is in the vicinity of the Round Hill Area. Stüwe & Ehlers (1997) recognized two distinct metamorphic events; an older event associated with the Olarian Orogeny and a younger event possibly associated with the Delamerian Orogeny. For clarity, we have only incorporated the first metamorphic event described by Stüwe & Ehlers (1997) into our
The first metamorphic event of Stüwe & Ehlers (1997) is associated with shortening during the early stages of the Olarian Orogeny at c. 1600 Ma, and occurred at conditions of 4–5 kbar and 650 °C. Metamorphism was followed by near-isobaric cooling that was interrupted by younger episodes of deformation. The overall P–T path is anticlockwise (Fig. 13).

In contrast, Swapp & Frost (2003) suggested the P–T path of the Broken Hill Block is clockwise, and that the peak metamorphic assemblage in the Round Hill pelites is defined by garnet + rutile + aluminosilicate + ilmenite. The presence of rutile in the assemblage implies higher-pressure conditions (at least 9 kbar) associated with temperatures of 775 °C. Swapp & Frost (2003) suggested that this high-pressure event was followed by high-temperature decompression at least down to conditions of 5.5 kbar at 750 °C (Fig. 13), which they suggest are conditions of the last equilibrated assemblage preserved in the pelites. Electron microprobe analysis revealed no rutile within the Round Hill pelites and all oxides analysed were ilmenite (Tables 1–3), giving no evidence of high-pressure metamorphism or a clockwise P–T path.

DISCUSSION

Within the Round Hill Area, two metamorphic events (M1 & M2), both associated with deformation, and
occurring prior to the onset of crustal shortening during the Oarian Orogeny have been identified. These events record burial, and the M2 event is associated with peak granulite facies metamorphism at c. 1.6 Ga (Page et al., 2000a). Whether these are completely separate tectonothermal events or part of a continuous $P$–$T$ path of heating and burial is difficult to distinguish. Perturbations in the geothermal gradient can assist in constraining the origin of these tectonothermal events, and can be inferred from calculating the geotherm at the conditions of the metamorphic events, as determined on a $P$–$T$ grid. Calculation of the approximate local geothermal gradients of the M1 and M2 events was done assuming 1 kbar of pressure equals a rock pile 3.5 km thick. The geothermal gradient of the M1 event was calculated to be between 41 and 61 °C km$^{-1}$, depending on the original pressure (c. 2.8–4.2 kbar at 600 °C; Fig. 13). The M2 event geothermal gradient was calculated to be 42 °C km$^{-1}$ (Fig. 13). Both the M1 and M2 events are therefore associated with elevated geothermal gradients (assuming a normal geotherm of 25 °C km$^{-1}$).

Prograde path A shown on Fig. 13 is drawn originating at higher pressure at the M1 event, and approximately follows the M1 geotherm of 41 °C km$^{-1}$ to peak M2 metamorphic conditions (Figs 13 & 14a). This path implies burial of 0.8 kbar, equivalent to 2.8 km of sediment between the M1 and M2 events (Fig. 14a). Path B (Fig. 13) originates at lower pressures, and implies burial of 2.2 kbar (c. 7.7 km sediment) between M1 and M2 (Fig. 14a). This path also moves to a shallower geotherm, implying that although the temperature of the rock package was becoming hotter towards conditions of peak metamorphism, the thermal gradient was decreasing (Figs 13 & 14a).

Understanding the origin of the elevated M1 geothermal gradient and the extent to which it was carried over into the M2 event is critical to modelling the prograde tectonic history of the Broken Hill Block. Elevated geothermal gradients may be the result of a number of reasons, including: (a) burial of anomalously high heat-producing rock packages (e.g. Chamberlain & Sonder, 1990; Sandiford & Hand, 1998; Sandiford et al., 1998; McLaren et al., 1999); (b) emplacement of voluminous granitoid sheets (e.g. Lux et al., 1986; Barton & Hanson, 1989; De Yoreo et al., 1989; Collins & Vernon, 1991); (c) heat flow into the base of the crust through magma underplating.
(convection) and/or emplacement of mantle or lower-crustal derived magmas into the lower crust (advection) (e.g. Bohlen, 1987, 1991; Bohlen & Mezger, 1989).

Elevation of the M1 geothermal gradient in response to burial of high heat-producing rock packages (e.g. U- and Th-rich sediments: Chamberlain & Sonder, 1990; highly radiogenic granites: Sandiford & Hand, 1998; Sandiford et al., 1998; McLaren et al., 1999) is not considered applicable, as no such anomalous sequence has yet been identified within the Broken Hill Block. Additionally, this scenario requires burial prior to heating, whereas the prograde path of the Round Hill pelites indicates heating prior to burial. Emplacement of voluminous granitoid sheets can also be eliminated as maintenance of high-temperature conditions would require granitoid intrusions to comprise up to 50% of the total rock package volume (Barton & Hanson, 1989; Collins & Vernon, 1991), and no such volume of granites intruded early in the evolution of the Broken Hill Block have been recognized. In a similar manner, attainment of high temperatures during metamorphism solely by intrusion of mafic magmas can be dismissed as voluminous mafics have not been recognized within the Broken Hill Block. Additionally, amphibolite bodies within the terrane yield ages of 1691 ± 9 Ma (e.g. Gibson & Nutman, 2004), which is much older than the timing of peak metamorphism (c. 1.6 Ga; Page et al., 2000a).

Demonstrative evidence for a magmatic underplate may be a long wavelength positive gravity anomaly, melt products with mantle signatures (e.g. picrites, peridotites, lherzolites), or depleted mantle isotopic signatures (e.g. Foden et al., 2002). Dismissal of elevation of the geothermal gradient as a result of a magmatic underplate because of lack of such evidence within the Broken Hill Block would require much caution as such signatures may have been obscured during the intense deformational and metamorphic history of the terrane during the Olarian and Delamerian Orogenies.

As a magmatic underplate cannot be unequivocally demonstrated within the Broken Hill terrane, we consider the setting in which magmatic underplating occurs, and whether the characteristics of such environments may be identified within the region. Magmatic underplating occurs in response to partial melting of the asthenosphere because of adiabatic decompression of the mantle (e.g. Van der Pluijm & Marshak, 1997). Asthenospheric decompression is most commonly considered a response of lithospheric thinning (e.g. Wyborn et al., 1988; Lister et al., 1991; Van der Pluijm & Marshak, 1997; Giles et al., 2002).

Lower units of the Broken Hill stratigraphy comprise quartzofeldspathic sequences grading into turbidites that were interpreted to be deposited within an evolving rift-basin (e.g. Stevens et al., 1988) c. 1.71–1.67 Ga (Page et al., 2000a). Gibson & Nutman (2004) suggested the timing of early rifting can be constrained to 1.69–1.67 Ga and ceased at the time of deposition of the uppermost rift sediments in the Broken Hill

Fig. 14. Schematic representation of tectonic histories and resultant geothermal gradients interpreted for the M1/D1 and M2/D2 prograde P–T path of the Broken Hill Block; (a) M1/D1 rifting c. 1.69–1.67 Ga; (b) M1/D1 rifting c. 1.64–1.61 Ga (see text for discussion).
stratigraphy (Sundown Group; Fig. 2), which have a maximum depositional age of c. 1.67 Ga (Page et al., 2000a). An early rifting event c. 1.69 Ga provides a mechanism by which the M1 geothermal gradient may have been raised. However, the timing of the M2/D2 event has been constrained to c. 1.6 Ga from the dating of peak metamorphic assemblages (Page et al., 2000a). Therefore, the mechanism of burial between the M1 and M2 events needs to be addressed, and the cause of the high temperatures of peak granulite facies metamorphism accounted for.

The increase in pressure of 0.8–2.2 kbar in the pro-grade $P$–$T$ path between the M1 and M2 events (Fig. 13) is interpreted to be in response to deposition of the Paragon Group sag-phase sediments (Fig. 2) from c. 1.66 to 1.6 Ga (Page et al., 2000a; Raetz et al., 2002). This pressure increase would require c. 2.5–7.5 km of sediment to be deposited. A more precise estimate of the required sedimentary thickness requires knowledge of the rock composition and density (e.g. Yardley, 1989). As neither the top of the Paragon Group in the Broken Hill Block, nor that of

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Fig. 14. (Cont’d)
the laterally equivalent rocks (Mount Howden Subgroup) in the neighbouring Olary Domain is exposed, no assessment of the thickness of the sedimentary pile during late sedimentation can be made. However, an analogy can be drawn from the Mount Isa Inlier, which has been suggested to have shared a similar tectonic history to the Broken Hill Block until c. 1.5 Ga (Giles et al., 2004), and within which equivalent units to the Paragon Group are the McNamara Group. The McNamara Group represents sag-phase sediments up to 8 km thick (Bettis et al., 1998; Southgate et al., 2000), deposited between 1.65 and 1.59 Ga (Page & Sweet, 1998; Page et al., 2000b) into the Isa Superbasin (Southgate et al., 2000). This possibly supports the interpretation that the Paragon Group may have been of sufficient thickness to provide enough sediment overburden to increase the pressure of the middle-crust by 0.8–2.2 kbar.

From prograde path A (Fig. 13), the period between the M1 and M2 events can be modelled as being burial in response to sag-phase sedimentation following early rifting c. 1.69 Ga. However, lithospheric thermal relaxation commonly follows rifting, and results in lowering the geothermal gradient (e.g. Morgan & Ramberg, 1987), and it is unlikely that the crustal pile would follow a constant geothermal gradient with increasing depth following rifting. A second deformation event at c. 1.6 Ga that would alter the thermal state of the crust during peak M2 metamorphism is also not considered in this scenario. As there is clear evidence of a second deformation event within the Round Hill Area, this model is not considered to fully account for the observations made.

Figure 14(a) shows two possible scenarios drawn from path B (Fig. 13) depicting the link between a 1.69 Ga M1/D1 rift event and the c. 1.6 Ga M2/D2 event. The first scenario models the D2 event as extensional (Fig. 14ai), and the second models a D2-thrusting event (Fig. 14aii). In the first model (Fig. 14ai), the lithosphere would have begun to subside and thermally relax at the cessation of c. 1.69–1.67 Ga rifting. As a result, the geothermal gradient of the lithosphere would have been reduced. A consequence of extension is that the geothermal gradient is raised, therefore, as the final M2/D2 geothermal gradient was c. 42 °C km⁻¹, the geothermal gradient within the Round Hill Area would have cooled to < 42 °C km⁻¹ during the interval between the M1/D1 and M2/D2 events (Fig. 14ai). Renewed extension during the M2/D2 event would have resulted in elevation of the cooled geothermal gradient back to 42 °C km⁻¹ (Fig. 14ai). Although the geothermal gradient was decreasing, the high temperatures of granulite facies metamorphism would have been attained during the M2 event as the temperature of the rock package would be maintained through burial, and would also have increased because of any additional heat input during D2 lithospheric thinning. This scenario can also be applied to path A (Fig. 13).

In the thrusting model (Fig. 14aii), burial and thermal relaxation following early rifting would have initiated cooling of the geotherm. As crustal thickening results in a decrease in the geothermal gradient, the geotherm during burial would have lowered to a value between 61 and 42 °C km⁻¹ (Fig. 14aii). Crustal thickening during thrusting at c. 1.6 Ga would have lowered the geothermal gradient further to c. 42 °C km⁻¹ (Fig. 14aiii). The high temperature of the rock package would have been maintained because of burial.

Although the two models described account for variations in temperature and thermal gradient during the prograde path of the Round Hill pelites, it is difficult to account for the pressure conditions of the M1 rift event (2.8–4.2 kbar) at 1.69–1.67 Ga as this is the time of deposition of the Sundown Group (Page et al., 2000a), and the Round Hill pelites are located across the boundary of the underlying Broken Hill Group (RHA59, RHA51) and Sundown (RHA58) Groups. Other possible scenarios for the early evolution of the Broken Hill Block could be that the M1/D1 event occurred closer to the time of the M2/D2 event c. 1.6 Ga as shown in Fig. 14(b). In these cases, the Sundown Group and parts of the Paragon Group would have already been deposited at the time of the M1/D1 event. The M1/D1 event is again interpreted as being extensional to account for the high geothermal gradient (Fig. 14b). A rift event c. 1.69–1.67 Ga is also included to account for basin evolution during deposition of the Willyma Supergroup (Fig. 14b) (Stevens et al., 1988). The M2/D2 event is also again interpreted as being either extensional (Fig. 14bi) or contractional (Fig. 14bii), and both interpretations are able to account for the temperatures and thermal gradient variations of the prograde path in ways similar to those described for the scenarios shown in Fig. 14(a). The implications of M2/D2 extension following rifting just prior this event are that the early evolution of the Broken Hill Block involved three transient episodes of extension separated by periods of sag-phase sedimentation and lithospheric thermal relaxation (Fig. 14bi). Only two episodes of transient extension are implied if the M2/D2 event involved thrusting (Fig. 14bii). In both cases, sag-phase sedimentation is terminated by the M2/D2 event c. 1.6 Ga; however, the nature of this event is unconstrained.

The M2 event is linked with high-temperature shear zones and development of the pervasive S2 fabric within the Round Hill Area. Determining whether these shear zones accommodated crustal thinning or thickening during the D2 event is difficult, as the prolonged and intense tectonothermal history of the Broken Hill terrane following peak metamorphism has obscured evidence of its kinematic significance. High-temperature, lithology-parallel shear zones have been described in other areas of the Broken Hill Block, and have been placed in extensional (e.g. Noble & Lister, 2001; Gibson & Nutman, 2004) and shortening (e.g.}

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White et al., 1995; Forbes & Betts, 2004) regimes. The distinguishing characteristic between the shear zones is that deformation related to shear zone activity in a shortening regime is associated with strain partitioning and recognizable folding attributed to the Olarian Orogeny. Shear zone activity at granulite facies conditions within the Round Hill Area is associated with development of the S2 fabric, which is folded by the first shortening event (D3) recognized in the area, and is interpreted to represent the early stage of the Olarian Orogeny. This lends towards the high-temperature shear zone being similar to other shear zones of an extensional origin, however does not unequivocally demonstrate it.

CONCLUSIONS

Two tectonothermal events, M1/D1 and M2/D2 occurred in the Broken Hill Block prior to the Olarian Orogeny. The M1/D1 event attained conditions of at least c. 600 °C at pressure of c. 2.8–4.2 kbar, and involved heating to attain a raised geothermal gradient (c. 41–61 °C km⁻¹). The M2/D2 event occurred at conditions of at least 740 °C at c. 5 kbar, and was associated with peak granulite facies metamorphism. These events were separated by an episode of burial of c. 0.8–2.2 kbar, depending on the original pressure conditions of the M1 event. The overall P–T path for the Broken Hill Block is antitropical.

The M1/D1 event is interpreted to be associated with rifting at either c. 1.69–1.67 Ga, during which time the Willyama Supergroup was deposited into an evolving basin, or at c. 1.64–1.61 Ga just prior to the M2/D2 event. The M1/D1 event was followed by a period of lithospheric thermal relaxation and burial during sag-phase sedimentation (Paragon Group). The M2/D2 event occurred c. 1.6 Ga, and involved development of lithology-parallel high-temperature shear zones and a regionally pervasive S2 fabric. Whether these shear zones were active within a crustal thinning or thickening environment remains unresolved. The D2 event was terminated by the onset of crustal shortening during the Olarian Orogeny.

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