Precambrian Research 166 (2008) 338–349

Contents lists available at ScienceDirect

Precambrian Research

journal homepage: www.elsevier.com/locate/precamres

Reinterpretation of the tectonic context of high-temperature metamorphism in the Broken Hill Block, NSW, and implications on the Palaeo- to Meso-Proterozoic evolution

C.J. Forbes[a,b,*], P.G. Betts[b], D. Giles[b], R. Weinberg[a,b]

[a] *Predictive Mineral Discovery Cooperative Research Centre, Australia*
[b] *School of Geosciences, Australian Crustal Research Centre, Monash University, Clayton, Vic 3800, Australia*

ARTICLE INFO

Article history:
Received 1 May 2006
Received in revised form
27 November 2006
Accepted 7 December 2006

Keywords:
Broken Hill
Metamorphism
Geothermal gradient
Extension
Orogenesis

ABSTRACT

The origin of high temperatures during regional low-pressure granulite facies metamorphism within the Proterozoic Broken Hill Block, Australia, has been reinterpreted to be the result of burial of anomalously hot rock packages for which the lithospheric geothermal gradient was initially elevated during early rifting ca. 1.71–1.67 Ga, and then maintained during a ca. 1.62 Ga short-lived mid-crustal extensional event. Mid-crustal extension at ca. 1.62 Ga was associated with amphibolite facies metamorphism and elevated lithospheric geothermal gradients, and occurred prior to activity along D2 high-temperature shear zones, peak low-pressure granulite facies metamorphism (ca. 1.60 Ga) and crustal shortening during the Olarian Orogeny (ca. 1.60–1.59 Ga). This reinterpretation places the Broken Hill Block within an environment in which multiple episodes of transient extension (ca. 1.71–1.62 Ga) were followed by a switch to shortening at ca. 1.60 Ga. The interpreted tectonic environment is a continental back-arc setting located in the overriding plate of a subduction zone along the southern margin of Palaeoproterozoic Australia.

1. Introduction

Shear zones are critical structures that accommodate mid-crustal deformation during both extension (e.g. metamorphic core complex; Lister and Davis, 1989) and shortening (e.g. Helvetic nappes, Switzerland; Ramsay et al., 1983). Additionally, as shear zones accommodate strain during deformation they can record kinematic evidence that may otherwise go unrecognised within less deformed rock packages. Therefore, shear zones are key structures in unravelling the tectonothermal history of complexly poly-deformed and metamorphosed terranes (e.g. Goodge et al., 1993; Passchier, 1994). However, delineation of the original tectonic context of shear zones within complexly deformed terranes is often hindered due to reactivation, deformation or metamorphism of the shear zones during later events. Understanding these structures also requires accounting for the overprinting events themselves, which can prove a difficult task in poly-deformed and metamorphosed orogens.

The Proterozoic Broken Hill Block, NSW (Fig. 1), is an example of a complexly deformed terrane for which the early tectonothermal evolution has been a subject of contention (e.g. Marjoribanks et al., 1980; Hobbs et al., 1984; Gibson and Nutman, 2004; Gibson et al., 2004). Early high-temperature shear zones have been recognised (e.g. White et al., 1995; Noble and Lister, 2001; Venn, 2001; Gibson and Nutman, 2004), but the tectonic regime under which they developed is poorly understood. This lack of understanding of the early shear zones development has been a stumbling block in attempts to understand the evolution of the Broken Hill Block, with consequences for the pressure and temperature evolution and crustal architecture of the terrane, and the extensional (ca. 1.71–1.62 Ga) and orogenic (ca. 1.60–1.59 Ga) phases of its history. In particular, the source of heat and the timing of onset of regional low-pressure granulite facies metamorphism (ca. 1.60 Ga; Page and Laing, 1992; Page et al., 2005) that appears temporally associated with orogenesis are not understood. The resolution of these issues will feed into further understanding the Broken Hill Block in a tectonic setting, and its relationship to other similar Australian terranes (e.g. Mount Isa) during the Proterozoic.

In this paper, we summarize the Proterozoic tectonothermal evolution of the Broken Hill Block in light of structural, metamorphic and geochronological analysis conducted within a high-temperature shear zone located in the south of the terrane (Forbes et al., 2005, 2007). We then consider the concept that high-temperature metamorphism during Proterozoic orogenesis in the Broken Hill Block is related to episodes of crustal extension closely followed by shortening, and discuss the influence the pre-

---

* Corresponding author at: Centre for Mineral Exploration Undercover, School of Earth and Environmental Sciences, University of Adelaide, Adelaide, SA 5005, Australia. Tel.: +61 8 8303 5482; fax: +61 8 8303 4347.
E-mail address: caroline.forbes@adelaide.edu.au (C.J. Forbes).

0301-9268/$ – see front matter. Crown Copyright © 2008 Published by Elsevier B.V. All rights reserved.
doi:10.1016/j.precamres.2006.12.017

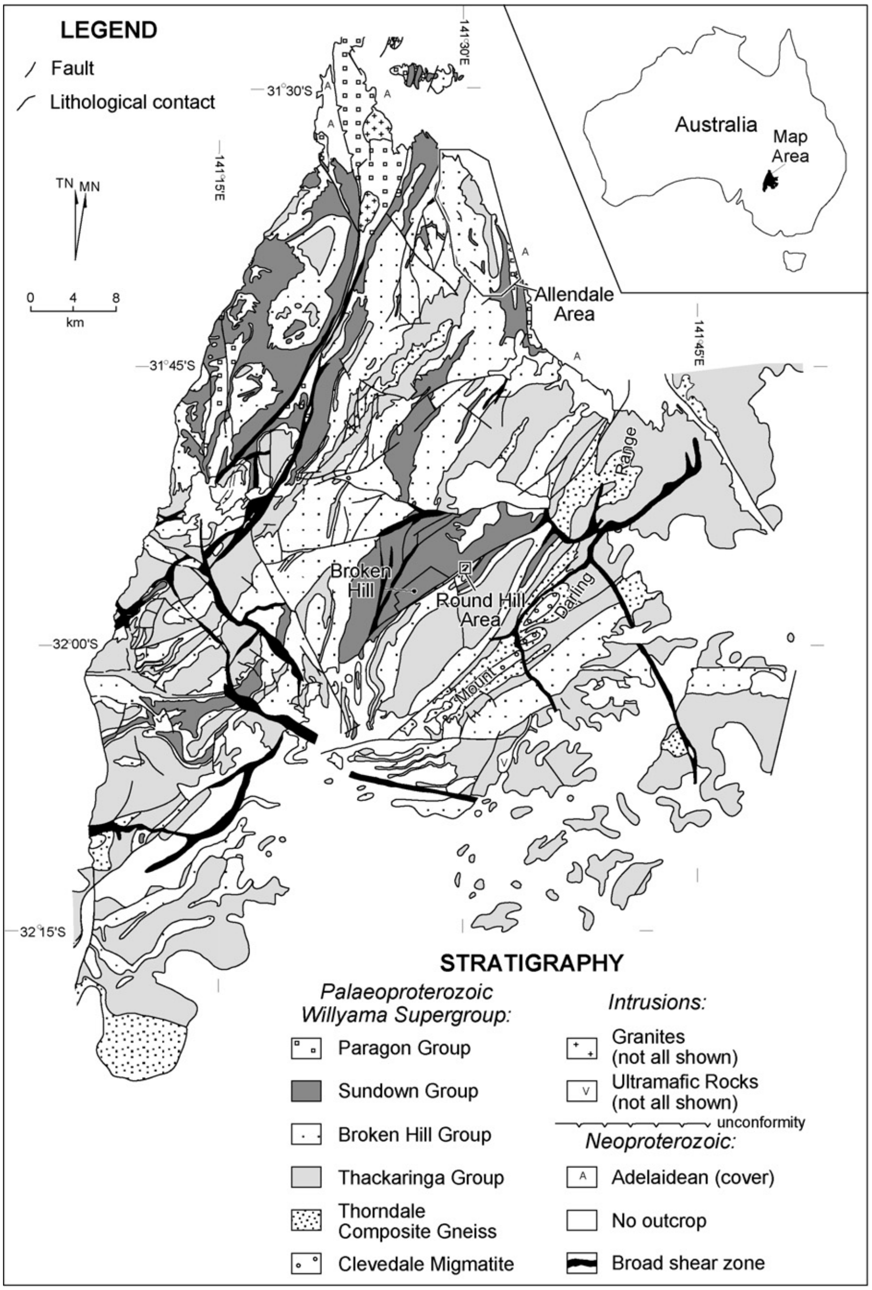

Fig. 1. Simplified geological map of the Broken Hill Block (modified after Willis et al., 1983).

shortening thermal regime and crustal architecture had on later deformation during orogenesis. Finally we review the implications of our conclusions for the Proterozoic plate-tectonic setting of the Broken Hill Block.

2. The Proterozoic tectonothermal evolution of the Broken Hill Block

The Broken Hill Block (Fig. 1) is comprised of the Willyama Supergroup (Fig. 2), the lower units of which were deposited into an evolving rift basin (e.g. Stevens et al., 1988) at ca. 1.71–1.67 Ga (Page et al., 2000a, 2005). Rifting was followed by sag-phase sedimentation and deposition of the Paragon Group of the upper Willyama Supergroup (Fig. 2) at least until ∼1.64 Ga (Page et al., 2000a, 2005) and possibly till 1.60 Ga (Raetz et al., 2002), however this is not known as if the sediments were deposited they have since been removed by erosion.

The basin into which the Willyama Supergroup was deposited was inverted during the Olarian Orogeny (ca. 1.60–1.59 Ga; Page et al., 2000a). Basin inversion involved complex polyphase deformation, and was closely associated with high-temperature/low-pressure metamorphism (Hobbs et al., 1984; Stevens et al., 1988). Peak amphibolite to granulite facies conditions were reached at ca. 1.60 Ga (Page and Laing, 1992), attaining pressures and temperatures of at least 740 °C at ∼5 kbar in the southern Broken Hill Block (Powell and Downes, 1990; Forbes et al., 2005). Due to the multiple and intense deformational and metamorphic events that affected the Broken Hill Block, the tectonothermal history of the terrane has been a subject of contention for many years, with

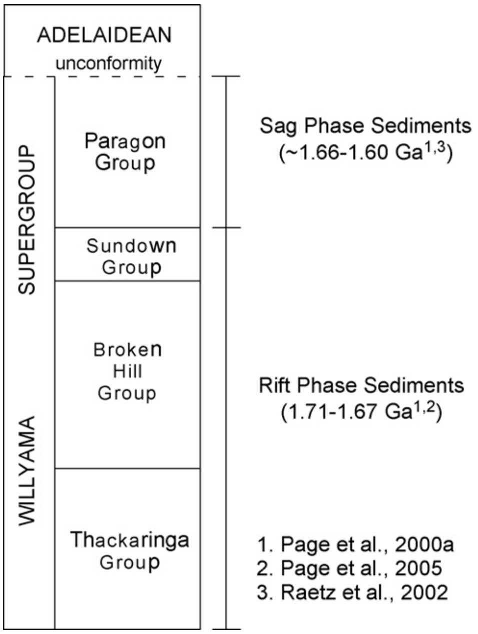

Fig. 2. Simplified stratigraphic column for the Willyama Supergroup (after Stevens et al., 1988).

several conflicting models depicting the tectonic architecture of the terrane throughout the Proterozoic (e.g. Marjoribanks et al., 1980; Hobbs et al., 1984; Stevens et al., 1988; White et al., 1995; Gibson and Nutman, 2004; Gibson et al., 2004, 2006; Connor et al., 2005; Stevens, 2006). A key part of this puzzle is the process that drove high-temperature/low-pressure metamorphism during crustal thickening (e.g. Hobbs et al., 1984; Loosveld and Etheridge, 1990; Forbes et al., 2005).

2.1. *Previous interpretations*

The earliest models depicting the geological evolution of the Broken Hill Block were based on regional-scale interpretations of stratigraphic relationships and folds (e.g. Marjoribanks et al., 1980; Hobbs et al., 1984). These models advocated an early generation of regional-scale nappe folds and it was inferred that the majority of the Broken Hill Block lay in the overturned limb of a D1 nappe (Marjoribanks et al., 1980) (Fig. 3). These nappes were overprinted by multiple generations of upright folds during the Olarian Orogeny (ca. 1.60–1.59 Ga; Page et al., 2000a) and the Delamerian Orogeny (∼520–490 Ma; Harrison and McDougall, 1981) (e.g. Marjoribanks et al., 1980; Hobbs et al., 1984; Webster, 1996; Wilson and Powell, 2001; Forbes et al., 2004; Forbes and Betts, 2004). The nappes have an axial planar fabric that is pervasive throughout the Broken Hill Block, occurs sub-parallel to lithological layering and is defined by a high-temperature sillimanite assemblage in pelitic lithologies (e.g. Marjoribanks et al., 1980; Hobbs et al., 1984). However, fold closures that are undeniably associated with this layer-parallel fabric have yet to be demonstrated.

White et al. (1995) reinterpreted the Broken Hill Block in terms of a mid-crustal fold and thrust belt, and suggested the terrane was deformed during a single progressive event under prograde metamorphic conditions (Fig. 3). In this model, the terrane was divided into several semi-independent thrust slices that underwent separate structural evolutions.

More recently, interpretations of an extensional history prior to the Olarian Orogeny have emerged. In these models, the early regionally pervasive high-temperature, lithology-parallel fabric recognised by Marjoribanks et al. (1980) and Hobbs et al. (1984) has been reinterpreted as extensional in origin and associated with an early phase of metamorphism and bimodal magmatism ca. 1.70–1.67 Ga (e.g. Gibson, 2000; Noble and Lister, 2001; Gibson and Nutman, 2004; Gibson et al., 2004) (Fig. 3). Early phases of extension are interpreted to have been accommodated along lithology-parallel high-temperature shear zones (e.g. Gibson and Nutman, 2004). Gibson and Nutman (2004) placed the Broken Hill Block in the context of a large-scale metamorphic core complex that was active at 1.69–1.67 Ga. In this model, extension was accommodated along a regionally extensive detachment located near the boundary of the Broken Hill and Sundown Groups (Fig. 2). Extension occurred contemporaneously with regional low-pressure/high-temperature metamorphism to amphibolite to granulite facies conditions, and resulted in development of the regionally pervasive, lithology-parallel fabric (Gibson and Nutman, 2004; Gibson et al., 2004). Gibson et al. (2004) suggested that early extension was followed by crustal thickening and development of large-scale, northwest-verging recumbent folding that was most intense at ca. 1.60 Ga. A second granulite facies event that attained peak metamorphic conditions within the Broken Hill Block accompanied this shortening. Further deformation resulted in northwest-directed thrusting and development of upright folds between 1.60 and 1.59 Ga (Gibson et al., 2004).

Gibson et al. (2004) introduced an early granulite facies event associated with extreme extension at 1.69–1.67 Ga (Fig. 3) and considered high-temperature/low-pressure metamorphism to be a response to crustal thinning, mantle upwelling and emplacement of voluminous magmas. In this model, it is difficult to account for the pressure conditions of the granulite facies event at 1.69–1.67 Ga, as this overlaps with the time of deposition of the sediments themselves (Sundown Group; Page et al., 2000a). This problem is also relevant to the proposal that the pervasive lithology-parallel high-temperature fabric preserved throughout the Broken Hill Block developed during extension at 1.69–1.67 Ga (Gibson et al., 2004), as the 1.69–1.67 Ga Sundown Group (Page et al., 2000a) also contains the early lithology-parallel sillimanite bearing fabric. The extreme extension associated with development of a metamorphic core complex would also be expected to have resulted in formation of characteristic extensional features (e.g. normal faults, wedge shaped stratal geometries, abrupt stratigraphic thickness changes) within the upper units of the Willyama Supergroup, in particular in the Sundown Group which was being deposited during the peak of extension. However, arguably such features would now be difficult to distinguish and identify due to the intense metamorphic and tectonic events that affected the Willyama Supergroup subsequent to its deposition.

2.2. *New data*

The interpretation of the Proterozoic evolution of the Broken Hill Block presented in this paper is a synthesis of recent structural, metamorphic and geochronological analysis conducted in the terrane by Forbes and Betts (2004), and Forbes et al. (2004, 2005, 2007). Forbes and Betts (2004) and Forbes et al. (2004) focused on the deformation elements (e.g. fold styles, fabrics) of the Olarian Orogeny. Deformation during this event was polyphase and involved complex reactivation of earlier formed high-temperature shear zones. Highly non-cylindrical (sheath-like) recumbent folds were identified through detailed structural analysis of the Allendale Area in the northern Broken Hill Block, and are interpreted to have developed during thin-skinned orogenesis in the early stages of shortening (Forbes et al., 2004). A high-temperature shear zone that was reactivated during the Olarian Orogeny and acted as a detachment structure and accommodated development of recum-

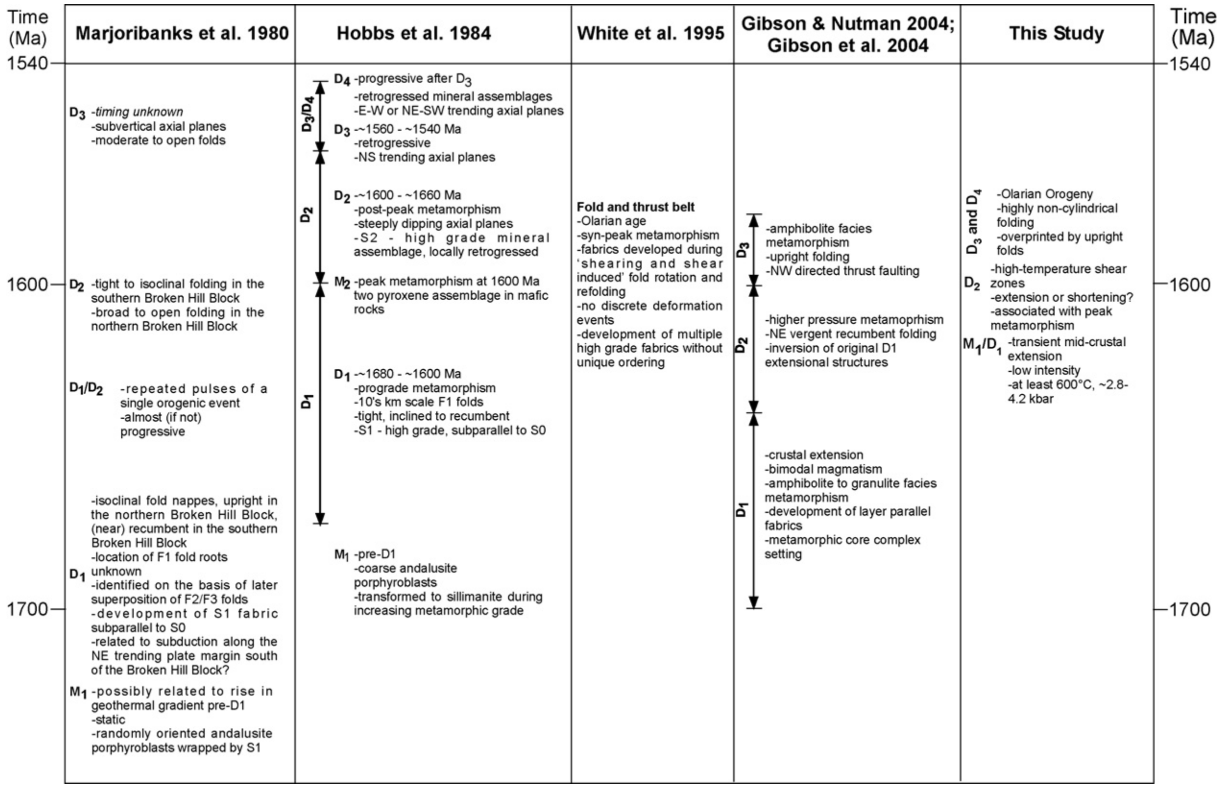

Fig. 3. Cladogram depicting previous interpretations and the interpretation made in this study of the Palaeo- to Meso-Proterozoic tectonothermal evolution of the Broken Hill Block (for more detail on this study see Fig. 5).

bent folds was also recognised (Forbes and Betts, 2004). These early folds were overprinted by ~north- to northeast-trending upright folds during thick-skinned deformation in the later stages of orogenesis (Forbes and Betts, 2004; Forbes et al., 2004). The overprinting of these fold generations was demonstrated to have resulted in generation of complex three-dimensional structural geometries throughout the Broken Hill Block (Forbes et al., 2004). These results generally confirm earlier interpretations of deformation events of the Olarian Orogeny (e.g. Marjoribanks et al., 1980; Hobbs et al., 1984); however a firm understanding of the effects of orogenesis is critical in identifying key structures that may have accommodated deformation prior to orogenesis and in determining the pre-shortening architecture and evolution of a complexly deformed terrane such as the Broken Hill Block.

Placing geochronological constraints on the pre-1.6 Ga tectonothermal evolution of the Broken Hill Block is difficult due to resetting of isotopic systems and recrystallisation of radiogenic minerals during peak granulite facies metamorphism at ~1.6 Ga. Nutman and Ehlers (1998) identified a zircon age population of 1.66–1.64 Ga from U-Pb SHRIMP dating. This age is interpreted to be a thermal pulse resulting in amphibolite to granulite facies metamorphism and melt segregation within the lower Willyama Supergroup. Teale and Fanning (2000) identified a ~1.63 Ga zircon age population that is attributed to a major albitisation event. These ages have not been readily accepted and have been suggested to be mixing ages (e.g. Page et al., 2000a, 2005; Stevens, 2000). More recently, Forbes et al. (2005, 2007) conducted a detailed structural, metamorphic and geochronological analysis of a high-temperature shear zone in the Round Hill Area of the southern Broken Hill Block (Fig. 1), interpreted to have developed prior to the Olarian Orogeny (Noble, 2000; Noble and Lister, 2001). *In situ* SHRIMP U-Pb geochronology of monazite from pelitic rocks sampled within the shear zone yielded an age population of ca. 1.62 Ga from grains completely enclosed within coarse-grained K-feldspar and garnet (Forbes et al., 2007). The host minerals comprise part of the peak granulite facies mineral assemblage preserved within the pelitic units, and the monazite inclusions occur with a biotite + sillimanite + plagioclase ± muscovite (M1 assemblage) that has been interpreted to have grown during prograde amphibolite facies metamorphism (Forbes et al., 2005). The ca. 1.62 Ga monazite age thus constrains the timing of prograde amphibolite facies metamorphism within the Broken Hill Block (Forbes et al., 2007).

Forbes et al. (2005) constrained the M1 inclusion assemblage to have grown at temperature and pressure conditions of at least 600 °C and ~2.8–4.2 kbar, corresponding to elevated lithospheric geothermal gradients of 41–61 °C/km. Elevated lithospheric geothermal gradients can occur in response to several causes: (i) burial of anomalously high heat producing rock packages (e.g. U- and Th-rich sediments: Chamberlain and Sonder, 1990; (ii) highly radiogenic granites: Sandiford and Hand, 1998; Sandiford et al., 1998; McLaren et al., 1999); (iii) emplacement of voluminous granitoid sheets (e.g. Lux et al., 1986; Barton and Hanson, 1989; De Yoreo et al., 1989; Collins and Vernon, 1991); (iv) heat convection/advection in to the lower crust through magma underplating or emplacement of magmas into the lower crust (e.g. Bohlen and Mezger, 1989; Bohlen, 1987, 1991). Forbes et al. (2005) suggested the first three scenarios could be ruled out in the Broken Hill Block as anomalously radiogenic rock units or sufficient volume of granite to account for the high temperatures of metamorphism have not been recognised in the terrane. Magmatic underplating commonly occurs in response to lithospheric thinning/extension and partial melting of the lithosphere during adiabatic decompression of the mantle (e.g. Wyborn et al., 1988; Lister et al., 1991; Van der Pluijm and Marshak, 1997; Giles et al., 2002). Extension in the Broken Hill Block is evidenced by quartzo-feldspathic and turbidite sequences interpreted to have been deposited within a rift environment ca. 1.71–1.67 Ga, and their association with bimodal volcanic rocks (e.g. Willis et al., 1983; Stevens et al., 1988). This evidence was also used by Gibson et al. (2004) to support their proposed earlier metamorphism at 1.70–1.67 Ga. The evidence of an active extensional regime in the Broken Hill Block, and the lack of high heat producing rock packages, highly radiogenic granites or voluminous granites was used by Forbes et al. (2005) to suggest the elevated lithospheric geothermal gradient of the M1/D1 event may have been a response to extension (Forbes et al., 2005).

2.3. The case for ca. 1.62 Ga mid-crustal extension

Determining the origin and significance of the ca. 1.62 Ga event is vital in delineating the Proterozoic tectonothermal evolution of the Broken Hill Block. Furthermore, this leads into understanding the heat source of high-temperature/low-pressure metamorphism at ca. 1.60 Ga, and can also be used to begin to understand the larger-scale plate-tectonic setting of the terrane at this time.

The crustal level at which the 1.62 Ga M1/D1 event occurred requires consideration. The defining fabric of the D1 event developed at amphibolite facies conditions, and is associated with pressures of ~2.8–4.2 kbar (~10–15 km). This would suggest the M1/D1 event occurred at mid-crustal levels, and these pressure conditions need to be accounted for. The pelites used in the Round Hill Area to estimate the pressure and temperature conditions of the M1/D1 event are close to the boundary of the Broken Hill and Sundown Groups (Bradley, 1980), and interpretations on the level of burial of the rock packages are taken from this stratigraphic location (Fig. 4). Up to 1.67 Ga, units of the Willyama Supergroup to the top of the Sundown Group (Fig. 2) were deposited (Page et al., 2000a). The type section of the Sundown Group is ~1.35-km thick (Willis et al., 1983) (0.4 kbar assuming 1 kbar = 3.5-km sediment). Therefore the Broken Hill Group/Sundown Group (BHG/SG) boundary was at approximately 1.35-km depth at ca. 1.67 Ga (Fig. 4). At this time, pressures and temperatures were not sufficient to account for the conditions estimated for M1 metamorphism (~2.8–4.2 kbar), and were also probably unfavourable for the development of the regionally pervasive sillimanite fabric preserved throughout the lower to middle units of the Willyama Supergroup (cf. Gibson et al., 2004). However, this is a *minimum* thickness estimate for the Sundown Group given the possibility for stratigraphic attenuation during deformation. In order for pressures to be consistent with the M1/D1 event (i.e. 2.8–4.2 kbar) at 1.67 Ga, the original thickness of the Sundown Group would have to be ~10–15 km. This thickness seems unlikely as it requires a factor of ~10 attenuation for the entire Sundown Group. The pressure conditions of the M1/D1 event at the BHG/SG boundary may have been attained by deposition of the sag-phase sediments of the Paragon Group from 1.66 to 1.64 Ga (Page et al., 2000a) and possibly up to 1.60 Ga (Raetz et al., 2002) (Fig. 4). The thickness of the Paragon Group is unknown as the top of the sequence is not exposed in the Broken Hill Block, nor is the top of laterally equivalent rocks (Mount Howden Subgroup) exposed in the neighbouring Olary Block. However, the Mount Isa Inlier, northern Australia, has been suggested as having undergone a similar tectonic history with the Broken Hill Block until ~1.50 Ga (Giles et al., 2004), therefore analogy might be drawn with this terrane. An equivalent unit to the Paragon Group is the McNamara Group, which represents a sequence of sag-phase sediments up to 8-km thick (Southgate et al., 2000; Betts et al., 1998) that were deposited between 1.65 and 1.59 Ga (Page and Sweet, 1998; Page et al., 2000b). If the stratigraphic pile was comparable to the Broken Hill Block, then the Paragon Group in combination with the Sundown Group sediments would have been of sufficient thickness to provide the sediment overburden to increase the pressure of the lower rock packages to the M1 pressure condi-

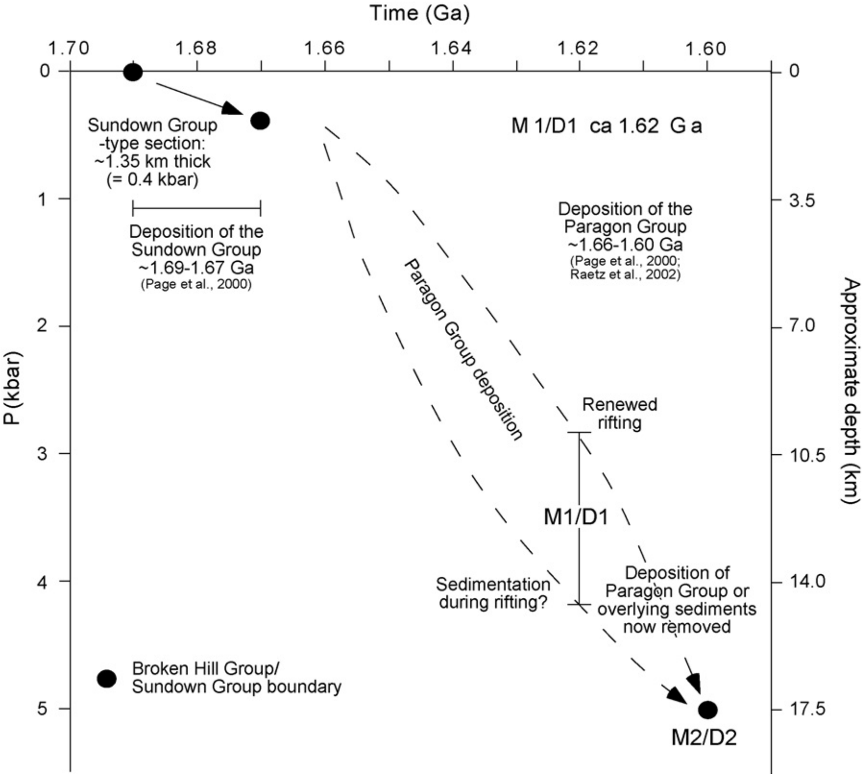

Fig. 4. Depth–time graph depicting the interpreted Proterozoic tectonothermal evolution of the Broken Hill Block based on rock units at the boundary of the Broken Hill and Sundown Groups (Fig. 2). At 1.67 Ga, the Broken Hill/Sundown Group boundary is at a *minimum* of 1.35 km depth (0.4 kbar) due to deposition of the Sundown Group. At 1.60 Ga the Broken Hill/Sundown Group boundary is at a depth of 17.5 km (~5 kbar). See text for further discussion.

tions (∼2.8–4.2 kbar, ∼10–15 km depth) estimated by Forbes et al. (2005) (Fig. 4).

Association of the ca. 1.62 Ga monazite inclusions with the M1 inclusion assemblage (Forbes et al., 2007) not only constrains the timing of prograde amphibolite facies metamorphism (Forbes et al., 2007), but also constrains the timing of the D1 event. Forbes et al. (2005) suggested the elevated lithospheric geothermal gradient of the M1 event may be a response to D1 being extensional, however there is no unequivocal evidence of extensional tectonics (e.g. normal faults) within the Broken Hill Block at this time. Demonstrating such evidence would be difficult due to the intense metamorphic and deformational history of the Broken Hill Block after 1.62 Ga, and also due to the M1/D1 tectonic fabric (S1) having only been recognised as inclusions preserved within garnet and K-feldspar porphyroblasts within a high strain zone (Forbes et al., 2005). The Mount Isa Inlier records multiple transient episodes of extension and basin development up to ∼1.62 Ga (e.g. Page et al., 2000b; Southgate et al., 2000; Betts et al., 2003, 2006). The similarities between the Mount Isa Inlier and the Broken Hill Block, as highlighted by Giles et al. (2004), suggests the Broken Hill Block may have occupied a basinal setting that experienced transient extensional episodes, which is akin to the setting of the Mount Isa Inlier at this time.

Identification of structures that may have accommodated an extensional event at ca. 1.62 Ga is difficult. However, Forbes et al. (2005) demonstrated that the S1 fabric is best preserved as inclusions within metamorphic porphyroblasts that are wrapped by an S2 shear fabric that defines a lithology-parallel high-temperature shear zone in the Round Hill Area (Fig. 1). This D2 shear zone was active during peak granulite facies metamorphism at ∼1.60 Ga (Forbes et al., 2007). The restriction of the S1 fabric to what are now recognised as D2 high strain zones indicates the possibility that these zones may have formed during the earlier D1 event, and were reactivated during the D2 event. However, this relationship has only been demonstrated within a single area, and the extreme conditions attained during peak metamorphism within the Broken Hill Block, as well as the intense overprinting of the shear zones during the Olarian and Delamerian Orogenies makes clear demonstration of earlier D1 shear zone development difficult.

The intensity of an extension event at ca. 1.62 Ga also remains uncertain. The lithospheric geothermal gradient of 41–61 °C/km calculated for the M1/D1 event (Forbes et al., 2005) is the earliest evidence of an elevated geotherm currently resolved within the Broken Hill Block. This elevated geotherm may be a primary feature, resultant solely from extreme mid-crustal extension at ca. 1.62 Ga; or may be reflective of an earlier event whereby a previously elevated geothermal gradient was maintained by transient extension during the 1.62 Ga M1/D1 event. In this latter case, the geothermal gradient may originally have become perturbed during the 1.69–1.67 Ga rifting event. Rifting at ca. 1.69–1.67 Ga may have involved a higher degree of extension, as reflected in the capacity of the resultant basin to accommodate deposition of the Willyama Supergroup stratigraphy, which is characterised as a deepening rift sequence (e.g. Willis et al., 1983; Stevens et al., 1988), with associated mafic (amphibolites: Nutman and Gibson, 1998; Page et al., 2000a) and felsic (Rasp Ridge Gneiss, Alma Gneiss: Page et al., 2000a) magmatism. The 1.62 Ga mid-crustal extensional event postulated in this study is not associated with any prominent extensional features (e.g. normal faults) or mafic and felsic magmatism, suggesting mid-crustal extension was not highly intense.

It is suggested that the 1.62 Ga M1/D1 event was a short-lived extensional event that may have been accommodated at mid-crustal levels along high-temperature shear zones that were later reactivated during D2 deformation. Thus, whilst the degree of extension may not have been sufficient to drive the lithospheric geothermal gradient to 41–61 °C/km in its own right, it may have been sufficient to maintain a previously elevated lithospheric geothermal gradient. The time of the M1/D1 event at 1.62 Ga occurs within the possible extended sag-phase of deposition of the Paragon Group (e.g. Raetz et al., 2002), however it is uncertain whether sedimentation continued during this transient event, or whether there was a small interval of depositional hiatus at ca. 1.62 Ga followed by further sedimentation.

2.4. Reinterpretation of the Proterozoic evolution of the Broken Hill Block

The Proterozoic evolution of the terrane prior to intense crustal shortening during the Olarian Orogeny (ca. 1.60–1.59 Ga; Page et al., 2000a) is considered to have been more complex than previously suggested, and is envisaged as having involved two extensional events (Fig. 5). This interpretation is based on previous structural, metamorphic and geochronological analysis of the Round Hill Area in the southern Broken Hill Block (Fig. 1) (Forbes et al., 2005, 2007).

The first phase of extension in the Broken Hill Block is the earliest stage of the geological history of the terrane, and has been previously described (e.g. Stevens et al., 1988). This event involved rifting and opening of the basin into which units of the Willyama Supergroup up to the top of the Sundown Group (Fig. 2) were deposited ca. 1.71–1.67 Ga. Rifting is evidenced by the progression of sediments deposited within a deepening environment throughout the Willyama Supergroup succession, and their association with mafic and felsic volcanics and intrusives (Willis et al., 1983; Stevens et al., 1988; Gibson and Nutman, 2004). An effect of rifting would have been elevation of the lithospheric geothermal gradient, however quantification of this has not yet been possible due to lack of data that may be used to estimate the geotherm at this time (e.g. primary mineral growth relationships that may be used to calculate the pressure and temperature conditions of a rock package and hence estimate the local geothermal gradient). Following early rifting, sag-phase sediments of the Paragon Group were deposited from ∼1.66 to 1.60 Ga (Page et al., 2000a; Raetz et al., 2002) (Fig. 5).

At ca. 1.62 Ga we suggest a transient mid-crustal extensional event (D1) affected the Broken Hill Block (Fig. 5). D1 occurred during prograde amphibolite facies metamorphism (M1) at temperatures and pressures of at least 600 °C and 2.8–4.2 kbar (Forbes et al., 2005), and may have been accommodated along early-formed mid-crustal shear zones.

In the Round Hill Area (Fig. 1), temperatures and pressures of at least 740 °C and ∼5 kbar (Powell and Downes, 1990; Forbes et al., 2005) were attained at ca. 1.60 Ga. This implies the rock packages were buried by ∼2.8–7.7 km of sediment (equivalent to 0.8–2.2 kbar) between ∼1.62 Ga (M1/D1) and ∼1.60 Ga (peak metamorphism) depending on the original pressure conditions of the M1 event (Fig. 4). This burial may be attributed to deposition of the upper units of the Paragon Group, or sedimentary rocks that overlie the Paragon Group and are no longer preserved in the rock record.

At ca. 1.60 Ga, peak granulite facies metamorphism (M2) occurred contemporaneously with activity along lithology-parallel high-temperature (D2) shear zones preserved throughout the Broken Hill Block (Forbes et al., 2005, 2007) (Fig. 5). The D2 shear zones characteristically display a moderately- to well-developed mineral lineation commonly defined by sillimanite + biotite (e.g. Noble, 2000; Gibson and Nutman, 2004; Forbes et al., 2005). Outside the shear zones, D2 is associated with the regionally pervasive, lithology-parallel high-temperature foliation defined by sillimanite + biotite (Forbes et al., 2005). As discussed by Forbes et al. (2005), whether activity along the D2 high-temperature shear zones and development of the associated regionally pervasive

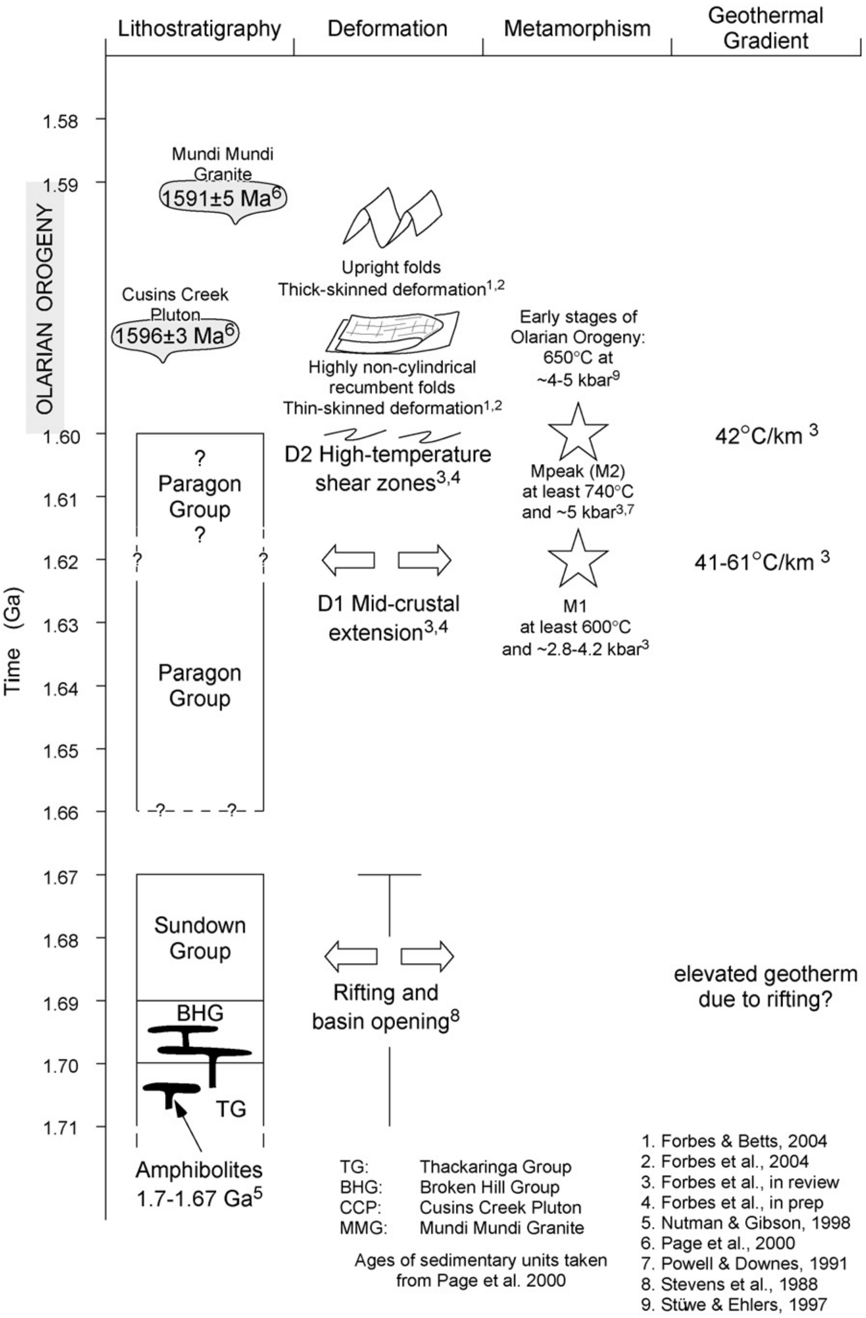

Fig. 5. Cladogram depicting the interpreted Proterozoic tectonothermal evolution of the Broken Hill Block.

high-temperature fabric at ca. 1.60 Ga was within an extensional or shortening regime is currently unresolved. The temperature and pressure conditions estimated for peak metamorphism (at least 740 °C at ~5 kbar; Forbes et al., 2005) imply the lithospheric geothermal gradient during metamorphism and activity along the shear zones was ~42 °C/km, which is most likely lower than that of the M1 event, even though the rock packages themselves were hotter (Forbes et al., 2005) (Fig. 5).

D2 deformation and peak metamorphism were closely followed by the Olarian Orogeny (ca. 1.60–1.59 Ga; Page et al., 2000a), which involved two main phases of folding (Fig. 5). Early phases of orogenesis resulted in development of highly non-cylindrical (sheath-like) recumbent folds associated with a high-temperature sillimanite fabric during thin-skinned thrusting deformation (Betts et al., 2002; Forbes et al., 2004; Forbes and Betts, 2004). Stüwe and Ehlers (1997) estimated temperature and pressure conditions in the Sundown Group north of Broken Hill to be ~650 °C and 4–5 kbar during this stage of orogenesis. The recumbent folds were subsequently overprinted by upright ~northeast trending folds during thick-skinned orogenesis (Marjoribanks et al., 1980; Hobbs et al., 1984; Forbes and Betts, 2004; Forbes et al., 2004), resulting in the development of complex fold interference patterns and three-dimensional structural geometries throughout the terrane (e.g. Hobbs et al., 1984; Forbes and Betts, 2004; Forbes et al., 2004). The pressure-temperature-deformation (*P*–*T*–*D*) path for the Proterozoic Broken Hill Block is anti-clockwise (Forbes et al., 2005). The long residence time of anti-clockwise *P*–*T* paths in the sillimanite field is attractive for this terrane as it accounts for the growth of abundant metamorphic sillimanite defining multiple fabrics within the pelitic units of the Willyama Supergroup (see also Bohlen, 1987).

The recognition of a discrete, datable thermal event at ca. 1.62 Ga provides additional constraint on the evolution of the Broken Hill Block in the crucial transition from extension to shortening and has implications for the mechanism of peak high-temperature/low-pressure granulite facies metamorphism at ca. 1.60 Ga. Additionally, with the resolution of two extensional events prior to orogenesis that follow an anti-clockwise *P–T–D* path, placing the Broken Hill Block into a larger tectonic setting calls for an environment within which multiple transient extensional events and a fast switch to intense crustal shortening can be explained. These issues are discussed in the following sections.

3. Influence of M1/D1 event on the thermal state of the crust during orogenesis

3.1. Inheritance of an elevated lithospheric geothermal gradient into orogenesis

The lithosphere is deemed to be in a steady thermal state when the internal production of heat within the lithosphere and the external input of heat from the underlying asthenosphere is equal to heat lost through the surface (Morgan and Ramberg, 1987). The return of a thermal perturbation within the lithosphere to a steady state is achieved through heat conduction through the lithosphere and eventual loss at the surface (e.g. Morgan and Ramberg, 1987). Therefore, the time for the lithosphere to re-equilibrate to a steady state is proportional to the depth of the heat source causing the thermal perturbation, which can be estimated from the equation $L^2/\pi^2\kappa$ (Carslaw and Jaeger, 1959; Lachenbruch and Sass, 1977), where L is the depth to the perturbation and κ is the thermal diffusivity. Approximating κ to be 10^{-6} m^2/s, Loosveld and Etheridge (1990) calculated that a homogeneously thinned lithosphere of a thickness of 150 km would have a crustal thermal relaxation time constant of ∼72 million years. This time constant decreases to 32 million years for a 100-km thick lithosphere (see also McKenzie, 1978). Using the same value for thermal diffusivity, for the time constant to be 20 million years (i.e. for the thermal perturbation associated with the M1/D1 event at ca. 1.62 Ga to have dissipated by the time of D2 deformation and the Olarian Orogeny at ∼1.60 to 1.59 Ga), the lithosphere would need to be thinned to ∼80 km.

However, this calculation assumes that the thermal anomaly associated with thinning was transient. If a thin lithosphere was maintained, or if the time constant was greater than 20 million years, then elevated geotherms from the extension phase may have been inherited during shortening. At the same time, the rock packages were being buried during sedimentation such that they became hotter (e.g. Birch et al., 1968), even if the geotherm was decreasing. Therefore, it is considered that the crust comprising what is now the Broken Hill Block was hot *prior* to deformation and orogenesis during the D2 event at ca. 1.60 Ga and the Olarian Orogeny (ca. 1.60–1.59 Ga; Page et al., 2000a) as a result of maintenance of a previously elevated geothermal gradient during transient mid-crustal extension at ca. 1.62 Ga. Burial of the hot crust resulted in an increase in temperature from ∼600 °C (ca. 1.62 Ga M1 temperatures; Forbes et al., 2005) to that of peak low-pressure granulite facies conditions (∼740 °C) at ca. 1.60 Ga.

3.2. The focussing of orogenesis within the Broken Hill Block

Rheological and thermal heterogeneities within the crust prior to orogenesis will influence strain localisation and the way in which deformation is accommodated (e.g. Tommasi and Vauchez, 1997; Vauchez et al., 1998; Thompson et al., 2001; Collins, 2002). Asthenospheric upwelling beneath continental rifts and arcs is considered a common cause of lithospheric thermal weakening (Thompson et al., 2001) as the geothermal gradient can be significantly modified. If shortening occurs soon after extension, a zone of crust weakened due to heating during rifting may become a preferential zone into which deformation is focussed (e.g. Thompson et al., 2001; Collins, 2002).

Evidence of an elevated geothermal gradient to 41–61 °C/km associated with M1/D1 mid-crustal extension at ca. 1.62 Ga (Forbes et al., 2005, 2007) implies the lithosphere would have been thermally weakened (e.g. Thompson et al., 2001). The Broken Hill Block may therefore have been the weaker part of the larger-scale crustal environment that would have accommodated a major portion of the strain within the plate at this time. Partitioning of strain during shortening into the Broken Hill Block shortly after the 1.62 Ga M1/D1 rift event is evidenced by the Olarian Orogeny (ca. 1.60–1.59 Ga; Page et al., 2000a). The intense deformation events of this period of orogenesis have resulted in development of complex overprinting relationships and structural geometries throughout the terrane.

The M1/D1 event may also have influenced the way in which deformation was accommodated during the Olarian Orogeny within the Broken Hill Block itself. Structures along which early rifting was accommodated would potentially have behaved as localised zones into which strain was partitioned during shortening, and if in a favourable orientation to the stress regime of later deformation, may be reactivated (e.g. Letouzey et al., 1990). It has been previously demonstrated that high-temperature shear zones were both folded (e.g. Broken Hill Synform Area; Noble and Lister, 2001) and reactivated (e.g. Allendale Mine Area; Forbes and Betts, 2004) during early phases of deformation associated with the Olarian Orogeny. These high-temperature shear zones would therefore have been pre-existing zones of weakness into which later deformation could be partitioned. If these high-temperature shear zones formed during the M1/D1 rift event, as has been postulated, this implies that within a terrane where rifting closely precedes orogenesis, the earlier event may influence the way in which strain is partitioned at the terrane-, to crustal-, to plate-scale.

4. Towards a tectonic model

The large-scale crustal architecture of the Broken Hill Block prior to orogenesis is difficult to discern as evidence of early deformation has been obscured during the Olarian Orogeny (ca. 1.60–1.59 Ga; Page et al., 2000a) and the Delamerian Orogeny (∼520–490 Ma; Harrison and McDougall, 1981). Previously, the terrane has only been considered in terms of an intra-continental setting (e.g. Stevens et al., 1988); however, the Broken Hill Block has recently been shown to have a similar history with other eastern Australian Proterozoic terranes, particularly the Mount Isa Inlier (Giles et al., 2004).

Both the Mount Isa Inlier and Broken Hill Block record a history of multiple transient extensional events that switch to intense crustal shortening and basin inversion at ca. 1.60 Ga. In the Broken Hill Block, extension was terminated by the Olarian Orogeny (ca. 1.60–1.59 Ga; Page et al., 2000a), and in the Mount Isa Inlier was terminated by the onset of the Isan Orogeny (ca. 1.60–1.50 Ga; e.g. Page and Bell, 1986; O'Dea et al., 1997; Betts et al., 2006; Giles et al., 2006). In both terranes, orogenesis involved early stages of thin-skinned deformation and the development of large-scale recumbent folds (e.g. Loosveld, 1989; Marjoribanks et al., 1980; Betts et al., 2000; Forbes et al., 2004), closely followed by thick-skinned deformation associated with upright folding (e.g. MacCready et al., 1998; Marjoribanks et al., 1980; Betts et al., 2000; Forbes et al., 2004). Peak metamorphism within the southeastern

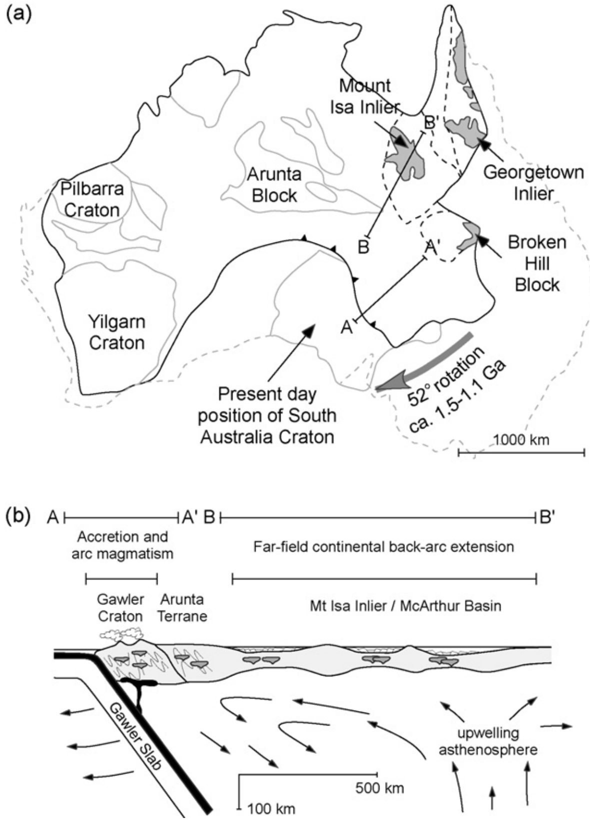

Fig. 6. (a) Schematic reconstruction of Proterozoic Australia following Giles et al., 2004; (b) schematic representation depicting the tectonic setting of northeastern Australia at ~1.8–1.6 Ga (Modified after Giles et al., 2002). The Mount Isa Inlier is situated within a far-field continental back-arc extensional setting, considered to be analogous to the setting of the Broken Hill Block at this time (see text for discussion).

Mount Isa Inlier attained upper amphibolite facies metamorphic grades (Jaques et al., 1982; Rubenach and Barker, 1998; Giles et al., 2006) culminating at ca. 1.60–1.58 Ga (Page and Sun, 1998; Giles and Nutman, 2002). Within the Broken Hill Block, peak metamorphism attained granulite facies conditions (e.g. Powell and Downes, 1990; Stüwe and Ehlers, 1997; Forbes et al., 2005) at ca. 1.60 Ga (Page and Laing, 1992).

In the case of the Mount Isa Inlier, early stages of basin evolution (ca. 1.8–1.67 Ga; Leichhardt and Calvert Superbasins of Jackson et al., 2000) have been placed into the context of a series of far-field continental back-arc basins that developed on the over-riding plate of a north-dipping subduction zone that lay parallel to the southern margin of the Proterozoic Australian continent (Giles et al., 2002, 2004; Betts et al., 2003; Betts and Giles, 2006) (Fig. 6a and b). Arc magmatism in the Arunta Inlier (1.77–1.75 Ga; Zhao and McCulloch, 1995) and later in the Gawler Craton (Ifould Complex, 1.74–1.67 Ga; Teasdale, 1997) is associated with subduction (Giles et al., 2002). In this model, the Proterozoic orogenic belts of eastern Australia are aligned (Fig. 6a) until 1.5 Ga when the South Australia Craton rotated 52° clockwise and reamalgamated with the West Australian Craton from ca. 1.5 to 1.1 Ga (Giles et al., 2004). Subsequent development of the Isa Superbasin (ca. 1.66–1.59 Ga) has also been attributed to activity along this subduction zone, but has additionally been linked with the opening of an oceanic basin to the east of the Proterozoic Australian continent (Betts et al., 2003; Betts et al., this volume). This complex extensional evolution prior to intense orogenesis within the Mount Isa Inlier places the terrane into the context of a plate-tectonic setting that is different from the previously envisaged intra-continental evolution of the terrane.

The close temporal association of stratigraphic deposition, magmatic activity and intense tectonothermal histories associated with orogenesis between the Broken Hill Block and Mount Isa Inlier (highlighted by Giles et al., 2002) raises the question as to whether pre-Olarian deformation within the Broken Hill Block was also a

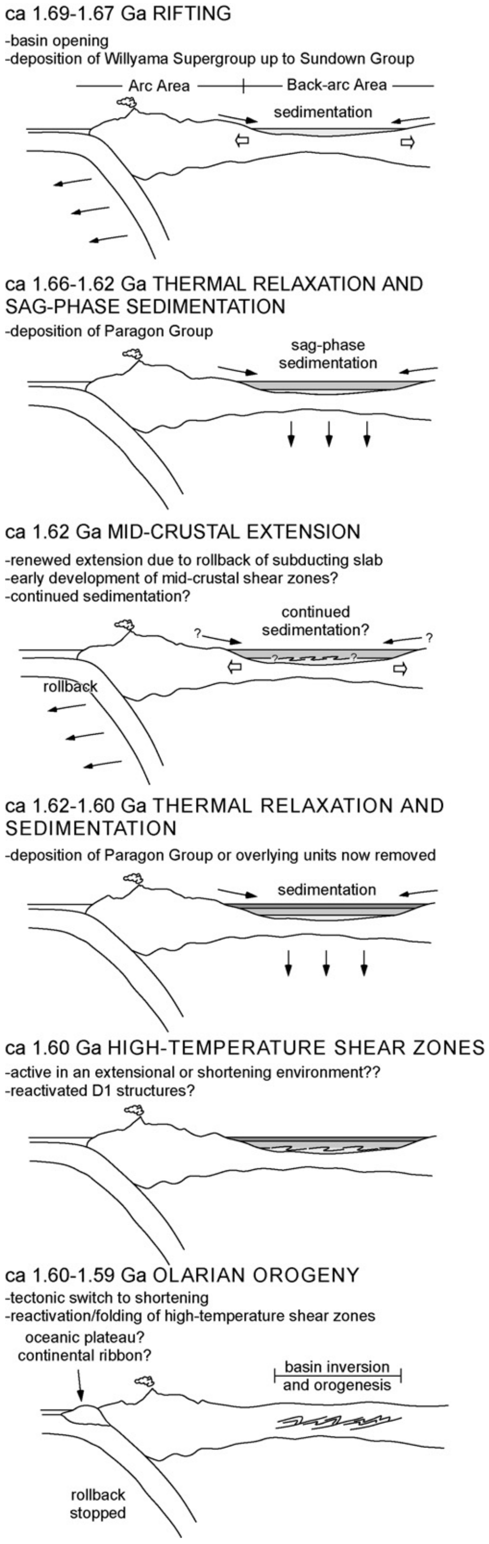

Fig. 7. Schematic representation of the Proterozoic evolution of the Broken Hill Block showing the Broken Hill Block in a continental back-arc setting within the over-riding plate of a subduction zone.

result of far-field stresses propagating through the over-riding plate of a subduction zone (Fig. 7), as opposed to an intra-continental rift environment (e.g. Stevens et al., 1988). Extension within the over-riding plate of a subduction zone may occur in response to slab-rollback (e.g. Central Volcanic Region, New Zealand: Stern, 1987; North Fiji Basin: Schellart et al., 2002). Additionally, an extensional setting accounts for the anti-clockwise *P*–*T* path followed during the Proterozoic evolution of the Broken Hill Block, and gives reason for elevation of the lithospheric geothermal gradient within the Broken Hill Block prior to peak metamorphism (Forbes et al., 2005, 2007). Within a subduction setting, a tectonic switch may occur in response to anomalously buoyant material (e.g. oceanic plateau) arriving at the site of subduction, throwing the system from a normally overall extensional environment into a short-lived compressional environment (Collins, 2002). Such a process will have no direct geological signature within the terrane of interest. This type of model has been applied to the Lachlan Orogen of eastern Australia to account for multiple episodes of extension and shortening throughout the history of the orogen (Collins, 2002). In the case of the Broken Hill Block, minor changes in plate motion, or accretion of continental ribbons at the site of subduction would throw the overall stress field from extensional (early basin opening at ca. 1.69 Ga (Stevens et al., 1988); mid-crustal extension at ca. 1.62 Ga (Forbes et al., 2007)) to shortening or possibly tectonic hiatus, accounting for periods of lithospheric thermal relaxation and sag-phase sedimentation (Paragon Group) (Fig. 7). At ca. 1.60 Ga, the overall stress field switched to shortening (Figs. 5 and 7). Thermal weakening of the crust due to elevation of the lithospheric geothermal gradient during earlier periods of extension would have made the Broken Hill Block a preferential zone into which deformation would have been focussed when the stress regime switched from extensional to shortening. In this case the Broken Hill Block could have been located a considerable distance from the actual plate margin. The interpretation that deformation in the Broken Hill Block resulted from plate boundary tectonic processes that induced far-field stresses through the crust is different from previously envisaged tectonic settings for the terrane.

5. Conclusions

The Broken Hill Block is considered to have undergone a more complex geological history than has been previously suggested, and involved at least two episodes of extension prior to intense crustal shortening. The first extensional event involved rifting and opening of a basin into which the Willyama Supergroup was deposited ca. 1.71–1.67 Ga (e.g. Page et al., 2000a, 2005). The Broken Hill Block then underwent burial to ∼10–15 km depth (2.8–4.2 kbar) during sag-phase sedimentation and deposition of the Paragon Group. The second transient extensional event (M1/D1) occurred at mid-crustal levels at ca. 1.62 Ga, and is associated with amphibolite facies conditions (at least 600 °C, ∼2.8 to 4.2 kbar) and an elevated lithospheric geothermal gradient. This elevated geotherm is suggested to have been inherited from an earlier extensional event (rifting at ca. 1.71–1.67 Ga) and was maintained at elevated levels during the short-lived 1.62 Ga M1/D1 mid-crustal extensional event. Following transient extension, the Broken Hill Block underwent further burial to ∼17.5 km depth (∼5 kbar). Burial of the hot rock packages resulted in temperatures increasing to conditions of peak regional low-pressure granulite facies metamorphism (∼740 °C, ∼5 kbar) at ∼1.60 Ga. Metamorphism is closely associated with the D2 event during which time a regionally pervasive sillimanite fabric developed. High-temperature shear zones were also active during the D2 event, and may have initially developed at this time, or may be reactivated D1 structures. Whether these shear zones developed within an extensional or shortening regime is unresolved. The D2 shear zones were later reactivated and refolded during the Olarian Orogeny (ca. 1.60–1.59 Ga).

With the resolution of a transient mid-crustal extensional event at ca. 1.62 Ga associated with elevated lithospheric geothermal gradients, the high temperatures of regional peak low-pressure granulite facies metamorphism at ∼1.60 Ga (Page and Laing, 1992) has been reconsidered to have been the result of burial of hot rock packages previously heated during earlier rifting and mid-crustal extensional events. Therefore, although the lithospheric geothermal gradient was decreasing due to thermal relaxation following extension, the temperature of the rock packages was increasing due to burial, eventually culminating in peak high-temperature granulite facies metamorphism at ∼1.60 Ga, just prior to the Olarian Orogeny. The elevated lithospheric geothermal gradient would also have resulted in thermal weakening of the crust comprising the Broken Hill Block, making the terrane a preferential site into which strain may have been partitioned at the plate-scale.

Reinterpretation of the Proterozoic tectonothermal history of the Broken Hill Block calls for a placing the terrane in a plate-tectonic setting that calls for environment in which multiple transient episodes of extension followed by a fast switch to intense crustal shortening can be accounted for. This tectonic environment may be in a back-arc setting located in the over-riding plate of a subduction zone, which supports previous suggestions for the setting of similar ages terranes (e.g. Mount Isa) during the Proterozoic.

Acknowledgements

This paper is published with permission of the CEO, pmd*CRC. Chris Doyle is thanked for helpful discussion. Constructive reviews by Toby Rivers and Huntley Cutten were much appreciated.

References

Barton, M.D., Hanson, R.B., 1989. Magmatism and the development of low-pressure metamorphic belts: implications from the western United States and thermal modelling. Geol. Soc. Am. Bull. 101, 1051–1065.

Betts, P.G., Giles, D., 2006. The 1800–1100 Ma tectonic evolution of Australia. Precambrian Res. 144, 92–125.

Betts, P.G., Lister, G.S., O'Dea, M.G., 1998. Asymmetric extension of the Middle Proterozoic lithosphere, Mount Isa terrane, Queensland, Australia. Tectonophysics 296, 293–316.

Betts, P.G., Aillères, L., Giles, D., Hough, M., 2000. Deformation history of the Hampden Synform in the Eastern Fold Belt of the Mount Isa terrane. Aust. J. Earth Sci. 47, 1113–1125.

Betts, P.G., Giles, D., Lister, G.S., Frick, L.R., 2002. Evolution of the Australian lithosphere. Aust. J. Earth Sci. 49, 661–695.

Betts, P.G., Giles, D., Lister, G.S., 2003. Tectonic environment of shale-hosted massive sulfide Pb–Zn–Ag deposits of Proterozoic northeastern Australia. Econ. Geol. 98, 557–576.

Betts, P.G., Giles, D., Mark, G., Lister, G.S., Goleby, B.R., Ailleres, L., 2006. A synthesis of the Proterozoic evolution of the Mount Isa Inlier. Aust. J. Earth Sci. 53, 187–211.

Birch, F., Roy, R.F., Decker, E.R., 1968. Heat flow and thermal history in New England and New York. In: Zen, E., White, W.S., Hadley, J.B. (Eds.), Studies of Appalachian Geology. Interscience, New York, pp. 437–451.

Bohlen, S.R., 1987. Pressure–temperature time paths and a tectonic model for the evolution of granulites. J. Geol. 95, 617–632.

Bohlen, S.R., Mezger, K., 1989. Origin of granulite terranes and the formation of the lowermost continental crust. Science 244, 326–329.

Bohlen, S.R., 1991. On the formation of granulites. J. Metamorph. Geol. 9, 223–229.

Bradley, G.M., 1980. Mount Gipps 1:25,000 Geological Sheet 7234 III S. Geological Survey of New South Wales, Sydney.

Carslaw, H.S., Jaeger, J.C., 1959. Conduction of Heat in Solids, 2nd edn. Clarendon Press, Oxford, 510 pp.

Chamberlain, C.P., Sonder, L.J., 1990. Heat-producing elements and the thermal and baric patterns of metamorphic belts. Science 250, 763–769.

Collins, W.J., 2002. Hot orogens, tectonic switching, and creation of continental crust. Geology 30, 535–538.

Collins, W.J., Vernon, R.H., 1991. Orogeny associated with anticlockwise P–T–t paths: evidence from low-P, high-T metamorphic terranes in the Arunta inlier, central Australia. Geology 19, 835–838.

Connor, C.H.H., Pries, W.V., Page, R.W., Stevens, B.P.J., Plimer, I.R., Ashley, P.M., 2005. Discussion on detachment faulting and bimodal magmatism in the Palaeoproterozoic Willyama Supergroup, south-central Australia: keys to recognition of a multiply deformed Precambrian metamorphic core complex. J. Geol. Soc. 162, 409–416.

De Yoreo, J.J., Lux, D.R., Guidotti, C.V., Decker, E.R., Osberg, P.H., 1989. The Acadian thermal history of western Maine. J. Metamorph. Geol. 7, 169–190.

Forbes, C.J., Betts, P.G., 2004. Development of Type 2 fold interference patterns in the Broken Hill Block: implications for strain partitioning across a detachment during the Olarian Orogeny. Aust. J. Earth Sci. 51, 173–188.

Forbes, C.J., Betts, P.G., Lister, G.S., 2004. Synchronous development of Type 2 and Type 3 fold interference patterns: evidence for recumbent sheath folds in the Allendale Area, Broken Hill, NSW, Australia. J. Struct. Geol. 26, 113–126.

Forbes, C.J., Betts, P.G., Weinberg, R., Buick, I.S., 2005. Metamorphism and high-temperature shear zones in the Broken Hill Block, NSW, Australia. J. Metamorph. Geol. 23, 745–770.

Forbes, C.J., Giles, D., Betts, P.G., Weinberg, R., Kinny, P., 2007. Dating prograde amphibolite and granulite facies metamorphism in the Broken Hill Block, NSW, using in situ monazite U-Pb SHRIMP analysis. J. Geol. 115, 691–705.

Gibson, G.M., Peljo, M., Chamberlain, T., 2006. Reply to comment by Brian Stevens on “Evidence and timing of crustal extension versus shortening in the early tectonothermal evolution of a Proterozoic continental rift sequence at Broken Hill, Australia”. Tectonics 25, TC4010.

Gibson, G.M., Nutman, A.P., 2004. Detachment faulting and bimodal magmatism in the Palaeoproterozoic Willyama Supergroup, south-central Australia: keys to recognition of a multiply deformed Precambrian metamorphic core complex. J. Geol. Soc. Lond. 161, 55–66.

Gibson, G.M., Peljo, M., Chamberlain, T., 2004. Evidence and timing of crustal extension versus shortening in the early tectonothermal evolution of a Proterozoic continental rift sequence at Broken Hill, Australia. Tectonics 23, TC5012.

Gibson, G.M., 2000. Tectonic evolution of the Palaeoproterozoic Willyama Supergroup, Broken Hill: the early years. Australian Geological Survey Organisation Record 2000/10, 45–47.

Giles, D., Nutman, A.P., 2002. SHRIMP U-Pb monazite dating of 1600–1580 Ma amphibolite facies metamorphism in the southeastern Mt Isa Block, Australia. Aust. J. Earth Sci. 49, 455–465.

Giles, D., Betts, P.G., Lister, G.S., 2002. Far-field continental backarc setting for the 1.80–1.67 Ga basins of northeastern Australia. Geology 30, 823–826.

Giles, D., Betts, P.G., Lister, G.S., 2004. 1.8–1.5-Ga links between the North and South Australian Cratons and the Early-Middle Proterozoic configuration of Australia. Tectonophysics 380, 27–41.

Giles, D., Betts, P.G., Ailleres, L., Hulscher, B., Hough, M., Lister, G.S., 2006. Evolution of the Isan Orogeny at the southeastern margin of the Mt Isa Inlier. Aust. J. Earth Sci. 53, 91–108.

Goodge, J.W., Hansen, V.L., Peacock, S.M., Smith, B.K., Walker, N.W., 1993. Kinematic evolution of the Miller Range shear zone, central Transantarctic Mountains, Antarctica, and implications for Neoproterozoic to early Paleozoic tectonics of the East Antarctic margin of Gondwana. Tectonics 12, 1460–1478.

Harrison, T.M., McDougall, I., 1981. Excess ^{40}Ar in metamorphic rocks from Broken Hill, New South Wales: implications for ^{40}Ar/^{39}Ar age spectra and the thermal history of the region. Earth Planet. Sci. Lett. 55, 123–149.

Hobbs, B.E., Archibald, N.J., Etheridge, M.A., Wall, V.J., 1984. Tectonic history of the Broken Hill Block, Australia. In: Kröner, A., Greiling, R. (Eds.), Precambrian Tectonics Illustrated. E. Schweizerbartische, Stuttgart, pp. 353–368.

Jackson, M.J., Scott, D.L., Rawlings, D.J., 2000. Stratigraphic framework for the Leichhardt and Calvert superbasins: review and correlations of the pre-1700 Ma successions between Mt Isa and McArthur River. Aust. J. Earth Sci. 47, 381–404.

Jaques, A.L., Blake, D.H., Donchak, P.J.T., 1982. Regional metamorphism in the Selwyn Range area, northwest Queensland. BMR J. Aust. Geol. Geophys. 7, 181–196.

Lachenbruch, A.H., Sass, J.H., 1977. Heat flow and the thermal regime of the crust. In: Heacock, J.G. (Ed.), The Earth’s Crust, its Nature and Physical Properties. American Geophysical Union, Washington DC, pp. 626–675.

Letouzey, J., Werner, P., Marty, A., 1990. Fault reactivation and structural inversion. Backarc and intraplate compressive deformations. Example of the eastern Sunda shelf (Indonesia). Tectonophysics 183, 341–362.

Lister, G.S., Davis, G.A., 1989. The origin of metamorphic core complexes and detachment faults formed during Tertiary continental extension in the northern Colorado River region, U.S.A. J. Struct. Geol. 11, 65–94.

Lister, G.S., Etheridge, M.A., Symonds, P.A., 1991. Detachment models for the formation of passive continental margins. Tectonics 10, 1038–1064.

Loosveld, R.J.H., 1989. The intra-cratonic evolution of the central eastern Mount Isa Inlier, Northwest Queensland, Australia. Precambrian Res. 44, 243–276.

Loosveld, R.J.H., Etheridge, M.A., 1990. A model for low-pressure facies metamorphism during crustal thickening. J. Metamorph. Geol. 8, 257–267.

Lux, D.R., De Yoreo, J.J., Guldotti, C.V., Decker, E.R., 1986. Role of plutonism in low-pressure metamorphic belt formation. Nature 323, 794–797.

MacCready, T., Goleby, B.R., Goncharov, A., Drummond, B.J., Lister, G.S., 1998. A framework of overprinting orogens based on interpretation of the Mount Isa deep seismic transect. Econ. Geol. 93, 1422–1434.

Marjoribanks, R.W., Rutland, R.W.R., Glen, R.A., Laing, W.P., 1980. The structure and tectonic evolution of the Broken Hill Region, Australia. Precambrian Res. 13, 209–240.

McKenzie, D., 1978. Some remarks on the development of sedimentary basins. Earth Planet. Sci. Lett. 40, 25–32.

McLaren, S., Sandiford, M., Hand, M., 1999. High radiogenic heat-producing granites and metamorphism—an example from the western Mount Isa Inlier, Australia. Geology 27, 679–682.

Morgan, P., Ramberg, I.B., 1987. Physical changes in the lithosphere associated with thermal relaxation after rifting. Tectonophysics 143, 1–11.

Noble, M., 2000. Geology of the Broken Hill Synform. M.Sc. Thesis. Monash University, Melbourne, unpublished.

Noble, M.P., Lister, G.S., 2001. Discovery of a km-scale early extensional shear zone that deformed the Broken Hill Pb–Zn–Ag orebody, NSW, Australia. Geol. Soc. Aust. Abstr. 64, 127–128.

Nutman, A.P., Ehlers, K., 1998. Evidence for multiple Palaeoproterozoic thermal events and magmatism adjacent to the Broken Hill Pb–Zn–Ag orebody, Australia. Precambrian Res. 90, 203–238.

Nutman, A.P., Gibson, G.M., 1998. Zircon ages from metasediments, granites and mafic intrusions: reappraisal of the Willyama Supergroup. AGSO Record 1998/25, 86–88.

O’Dea, M.B., Lister, G.S., MacCready, T., Betts, P.G., Oliver, N.H.S., Pound, K.S., Huang, W., Valenta, R.K., 1997. Geodynamic Evolution of the Proterozoic Mount Isa terrain. Orogeny Through Time, vol. 121. Geological Society, London, Special Publication, pp. 99–122.

Page, R.W., Bell, T.H., 1986. Isotopic and structural responses of granite to successive deformation and metamorphism. J. Geol. 94, 365–379.

Page, R.W., Laing, W.P., 1992. Felsic metavolcanic rocks related to the Broken Hill Pb–Zn–Ag orebody, Australia: geology, depositional age, and timing of high-grade metamorphism. Econ. Geol. 87, 2138–2168.

Page, R.W., Sun, S., 1998. Aspects of geochronology and crustal evolution in the Eastern Fold Belt, Mt Isa Inlier. Aust. J. Earth Sci. 45, 343–362.

Page, R.W., Sweet, I.P., 1998. Geochronology of basin phases in the western Mt Isa Inlier, and correlation with the McArthur Basin. Aust. J. Earth Sci. 45, 219–232.

Page, R.W., Stevens, B.P.J., Gibson, G.M., Conor, C.H.H., 2000a. Geochronology of Willyama Supergroup rocks between Olary and Broken Hill, and comparison to Northern Australia. Australian Geological Survey Organisation Record 2000/10, 72–75.

Page, R.W., Jackson, M.J., Krassay, A.A., 2000b. Constraining sequence stratigraphy in north Australian basins: SHRIMP U-Pb zircon geochronology between Mt Isa and McArthur River. Aust. J. Earth Sci. 47, 431–459.

Page, R.W., Stevens, B.P.J., Gibson, G.M., 2005. Geochronology of the sequence hosting the Broken Hill Pb–Zn–Ag orebody, Australia. Econ. Geol. Bull. Soc. Econ. Geol. 100, 633–661.

Passchier, C.W., 1994. Structural geology across a proposed Archaean terrane boundary in the eastern Yilgarn craton, Western Australia. Precambrian Res. 68, 43–64.

Powell, R., Downes, J., 1990. Garnet porphyroblast-bearing leucosomes in metapelites: mechanisms, phase diagrams, and an example from Broken Hill, Australia. In: Ashworth, J.R., Brown, M. (Eds.), High-temperature Metamorphism and Crustal Anatexis. Unwin Hyman Ltd., pp. 105–123.

Raetz, M., Krabbendam, M., Donaghy, A.G., 2002. Compilation of U-Pb zircon data from the Willyama Supergroup, Broken Hill region, Australia: evidence for three tectonostratigraphic successions and four magmatic events? Aust. J. Earth Sci. 49, 965–983.

Ramsay, J.G., Casey, M., Kligfield, R., 1983. Role of shear in development of the Helvetic fold-thrust belt of Switzerland. Geology 11, 439–442.

Rubenach, M.J., Barker, A.J., 1998. Metamorphic and metasomatic evolution of the Snake Creek Anticline, Eastern Succession. Mt Isa Inlier. Aust. J. Earth Sci. 45, 363–372.

Sandiford, M., Hand, M., 1998. Australian Proterozoic high-temperature, low-pressure metamorphism in the conductive limit. In: Treloar, P.J., O’Brien, P.J. (Eds.), What Drives Metamorphism and Metamorphic Relations?, 138. Geological Society, London, pp. 109–120, Special Publications.

Sandiford, M., Hand, M., McLaren, S., 1998. High geothermal gradient metamorphism during thermal subsidence. Earth Planet. Sci. Lett. 163, 149–165.

Schellart, W.P., Lister, G.S., Jessell, M.W., 2002. Analogue modelling of arc and backarc deformation in the New Hebrides arc and North Fiji Basin. Geology 30, 311–314.

Southgate, P.N., Bradshaw, B.E., Domagala, J., Jackson, M.J., Idnurm, M., Krassay, A.A., Page, R.W., Sami, T.T., Scott, D.L., Lindsay, J.F., McConachie, B.A., Tarlowski, C., 2000. Chronostratigraphic basin framework for Palaeoproterozoic rocks (1730–1575 Ma) in northern Australia and implications for base-metal mineralisation. Aust. J. Earth Sci. 47, 461–483.

Stern, T.A., 1987. Asymmetric back-arc spreading, heat flux and structure associated with the Central Volcanic Region of New Zealand. Earth Planet. Sci. Lett. 85, 265–276.

Stevens, B.P.J., 2000. Evaluating models for tectonic development of the Willyama Supergroup. Australian Geological Survey Organisation Record 2000/10, 87–90.

Stevens, B.P.J., 2006. Comment on “Evidence and timing of crustal extension versus shortening in the early tectonothermal evolution of a Proterozoic continental rift sequence at Broken Hill, Australia” by G.M. Gibson, M. Peljo, and T. Chamberlain. Tectonics 25, TC4009.

Stevens, B.P.J., Barnes, R.G., Brown, R.E., Ströud, W.J., Willis, I.L., 1988. The Willyama Supergroup in the Broken Hill and Euriowie Blocks, New South Wales. Precambrian Res. 40–41, 297–327.

Stüwe, K., Ehlers, K., 1997. Multiple metamorphic events at Broken Hill, Australia. Evidence from Chloritoid-bearing paragenesis in the Nine-Mile Mine Region. J. Petrol. 38, 1167–1186.

Teale, G.S., Fanning, C.M., 2000. The timing of Cu–Au mineralisation in the Curnamona Province. AGSO Record 2000/10, 72–75.

Teasdale, J., 1997. Methods for understanding poorly exposed terranes: The interpretative geology and tectonothermal evolution of the western Gawler Craton. Unpublished Ph.D. Thesis. University of Adelaide, Australia.

Thompson, A.B., Schulmann, K., Jezek, J., Tolar, V., 2001. Thermally softened continental extensional zones (arcs and rifts) as precursors to thickened orogenic belts. Tectonophysics 332, 115–141.

Tommasi, A., Vauchez, A., 1997. Continental-scale rheological heterogeneities and complex intraplate tectono-metamorphic patterns: insights from a case-study and numerical models. Tectonophysics 279, 327–350.

Van der Pluijm, B.A., Marshak, S., 1997. Earth Structure: An Introduction to Structural Geology and Tectonics. McGraw-Hill.

Vauchez, A., Tommasi, A., Barruol, G., 1998. Rheological heterogeneity, mechanical anisotropy and deformation of the continental lithosphere. Tectonophysics 296, 61–86.

Venn, C.J., 2001. The geodynamic evolution of the Mount Robe and Mount Franks region, Broken Hill Australia: Discovery of crustal-scale extensional shear zones and giant sheath folds. Ph.D. Thesis. Monash University, Melbourne, unpublished.

Webster, A.E., 1996. Delamerian refolding of the Palaeoproterozoic Broken Hill Block. Aust. J. Earth Sci. 43, 85–89.

White, S.H., Rothery, E., Lips, A.L.W., Barclay, T.J.R., 1995. Broken Hill area, Australia, as a Proterozoic fold and thrust belt: implications for the Broken Hill base-metal deposit. Trans. Inst. Mining Metall. Section B: Appl. Earth Sci. 104, B1–B17.

Willis, I.L., Brown, R.E., Ströud, W.J., Stevens, B.P.J., 1983. The Early Proterozoic Willyama Supergroup: stratigraphic subdivision and interpretation of high to low-grade metamorphic rocks in the Broken Hill Block, New South Wales. J. Geol. Soc. Aust. 30, 195–224.

Wilson, C.J.L., Powell, R., 2001. Strain localisation and high-grade metamorphism at Broken Hill, Australia: a view from the Southern Cross area. Tectonophysics 335, 193–210.

Wyborn, L.A.I., Page, R.W., McCulloch, M.T., 1988. Petrology, geochronology and isotope geochemistry of the post-1820 Ma granites of the Mount Isa Inlier: mechanisms for the generation of Proterozoic anorogenic granites. Precambrian Res. 40–41, 509–541.

Zhao, J., McCulloch, M.T., 1995. Geochemical and Nd isotopic systematics of granites from the Arunta inlier, central Australia: implications for Proterozoic crustal evolution. Precambrian Res. 71, 265–299.