Crustal architecture during the early Mesoproterozoic Hiltaba-related mineralisation event: are the Gawler Range Volcanics a foreland basin fill?

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Introduction

The tectonic setting of Hiltaba Suite (1595–1575 Ma) magmatism within the Gawler Craton has long been regarded as anorogenic, accompanied by mild extension (Flint et al. 1993; Creaser 1995). This evaluation was largely based on the apparently limited deformation recorded within the Hiltaba Suite and Gawler Range Volcanics, their enriched geochemical signature and the high-temperature nature of magmatism. However, there is now growing evidence that contractional fault reactivation, metamorphism and locally pervasive deformation were associated with the emplacement of the Hiltaba Suite and the associated iron oxide – copper–gold (IOCG) ± uranium and gold mineral systems, suggesting the existence of a compressional regime in the early Mesoproterozoic Gawler Craton. In this contribution, we briefly summarise evidence for crustal-scale early Mesoproterozoic deformation in the Gawler Craton and suggest it forms part of a broader system that incorporates the Olarian Orogeny of the Curnamona Province. In the light of the new data on the spatial nature of early Mesoproterozoic deformation and metamorphism across southern Australian Proterozoic terranes (Fig. 1), we suggest that the Gawler Range and Benagerie volcanics are an unusual volcanic-fill within a foreland basin that formed within a broadly NW–SE-directed compressional regime.

Several lines of evidence suggest that the Gawler Craton and the Curnamona Province were part of a coherent and likely contiguous, crustal system by the late Palaeoproterozoic to early Mesoproterozoic. In brief, these are: (1) likely correlation of the Gawler Range and Benagerie volcanics; (2) similarities in timing of early Mesoproterozoic granitic magmatism; and (3) growing evidence in the Gawler

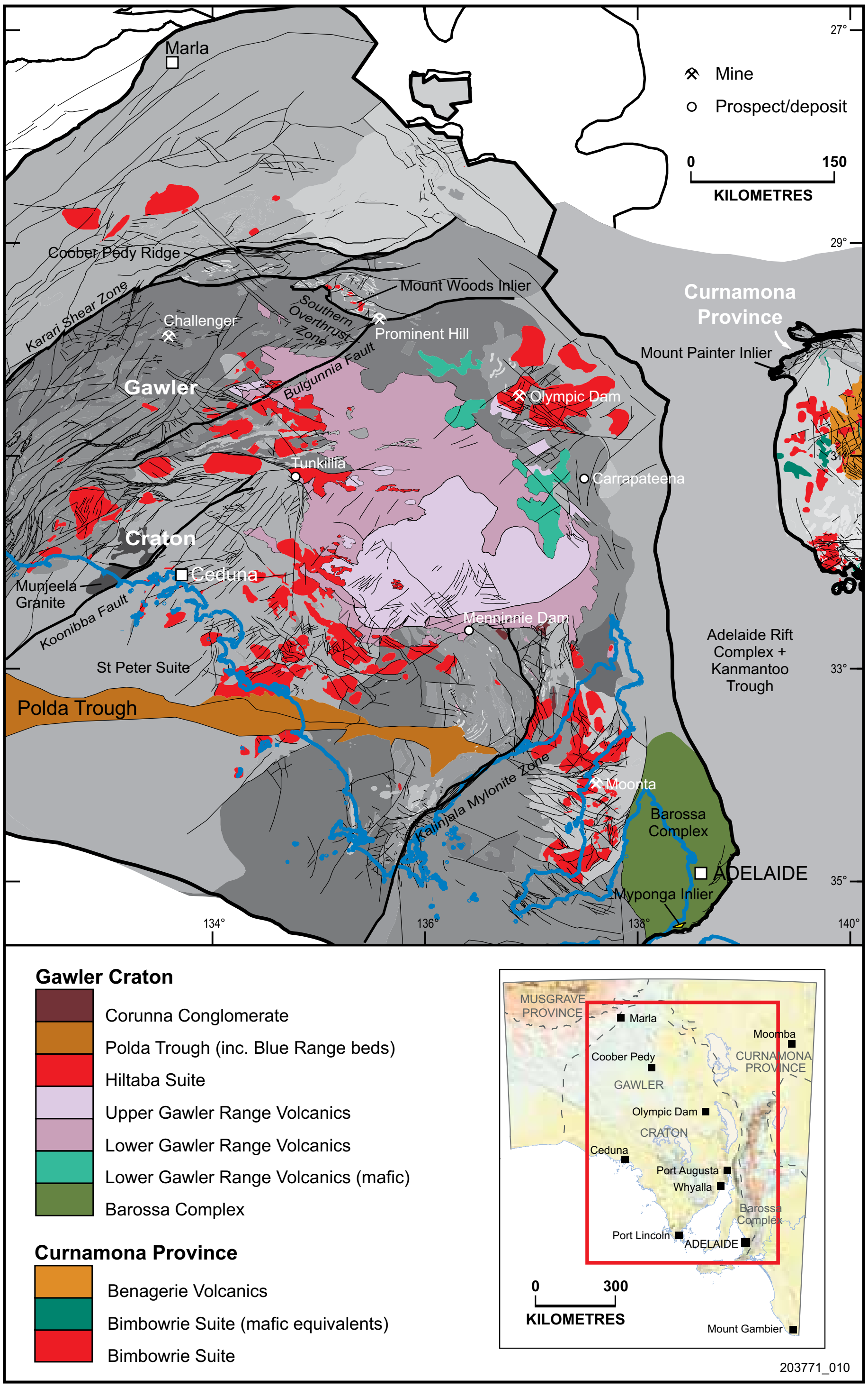

Figure 1 *Locality map of southern Australian Proterozoic terranes, including the Gawler Craton, Barossa Complex and Curnamona Province. Mesoproterozoic sequences and suites are highlighted; remaining solid geology is shown in grey-scale (after Cowley 2006). Also shown are major faults active during the Mesoproterozoic.*

Craton for sedimentation of equivalent age to the Willyama Supergroup of the Curnamona Province (Skirrow et al. 2006). The 1600–1585 Ma Olarian Orogeny in the Curnamona Province (Page et al. 2005) is generally regarded as the principal manifestation of regional early Mesoproterozoic deformation in southern Australia. However, there is now evidence for a much more extensive early Mesoproterozoic (1600–1560 Ma) deformation system in southern Australian Proterozoic terranes, which also involved the Gawler Craton and the associated Barossa Complex. Although some of this evidence has been available previously, there has been little evaluation of the regional extent of this compressional deformation within southern Australian Proterozoic terranes, nor of the implications for the distribution of the Gawler Range Volcanics and nature of the basin they occupy. We firstly review the characteristics of synorogenic sedimentary basins before examining the growing evidence for synorogenic sedimentation within southern Australia Proterozoic terranes during the Hiltaba-related mineralisation event.

Foreland basin terminology and systematics

A foreland basin system is defined as an elongate region of potential sediment accommodation that forms on continental crust between a contractional orogenic belt and the adjacent less deforming lithosphere (Allen and Homewood 1986; DeCelles and Giles 1996). The accommodation space reflects the flexural response associated with the development of the orogenic wedge load. Peripheral forelands, e.g. the Indo-Gangetic Plain along the southern margin of the Himalayas and north Alpine foreland in central Europe, need not be spatially associated with an active subduction system and can form entirely intracratonically. Retroarc systems are located behind an active magmatic arc linked with subduction (e.g. Mesozoic–Cenozoic Andean basins; Fig. 2). Both these types are commonly non-marine basins that form on cratonic lithosphere, and are associated with shortening in the adjacent tectonically active zones (DeCelles and Giles 1996; Allen and Allen 2005).

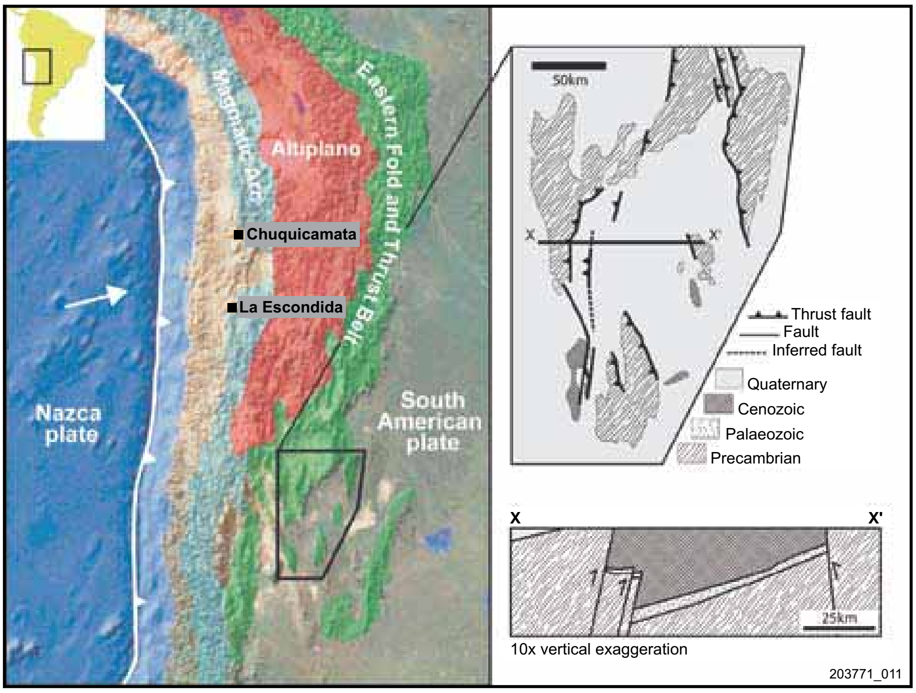

***Figure 2** Geological setting of synorogenic basin sequences of the Andes. Main map modified from Riller and Onocken (2003). Inset shows the La Rioja Basin and highlights the occurrence of synorogenic sedimentation and the development of bi-vergent thrusting, including exhumation of Precambrian rocks over Quaternary sediments in a back-arc setting. Inset modified from Fisher, Jordan and Brown (2002).*

Typically, the longitudinal dimension of a foreland basin system is roughly equal to the length of the associated deformation belt. The width of the foreland basin and the scale of the depocentre is a function of lithospheric strength, with narrow, deep basins reflecting weak lithosphere and broad, shallow basins reflecting strong lithosphere. Over the duration of deformation, the shape and extent of the basin may change as the dynamics of the orogen change. For example, deformation may prograde out into the foreland (e.g. DeCelles and Giles 1996), or may retreat into the hinterland (e.g. Haines, Hand and Sandiford 2001) with time.

Early Mesoproterozoic compressional deformation in the Gawler Craton and Barossa Complex

In the central and northeastern Gawler Craton, both the Tarcoola Formation (c. 1650 Ma), and metasedimentary packages in the Mount Woods region (<1670 Ma; Skirrow et al. 2006) have undergone pervasive NW–SE-directed shortening (Betts, Valenta and Finlay 2003). In the Mount Woods region deformation was associated with the formation of granulite-facies mineral assemblages (Chalmers 2007). In metapelitic rocks, initial garnet–andalusite-bearing assemblages were progressively replaced by cordierite–spinel, sillimanite, and then garnet, leading to peak (c. 730 °C, 4–5 kbar) assemblages of garnet–cordierite–biotite–K-feldspar–plagioclase–quartz, with local quartz-absent cordierite–spinel domains. This sequence of mineral growth requires a modest pressure increase, consistent with crustal thickening. Existing SHRIMP U–Pb data from metamorphic zircon gives ages between 1595–1583 Ma (Skirrow et al. 2006; Jagodzinski et al. 2007), indicating that deformation was synchronous with emplacement of the Hiltaba Suite.

These early Mesoproterozoic high-grade rocks stand in contrast to the weakly metamorphosed to unmetamorphosed rocks in the vicinity of the Prominent Hill Cu–Au deposit and extending further south towards the main body of the Gawler Range Volcanics. The boundary between these high- and low-grade rocks is the Bulgunnia Fault in the SE, and the Southern Overthrust Zone (Betts, Valenta and Finlay 2003) in the SW, the latter being equivalent to the Fitzgerald Shear of Belperio, Flint and Freeman (2007; Fig. 1). Given the relative metamorphic grade of the rocks on either side of these fault systems, it is clear that they must contain a significant component of vertical displacement, likely the result of bulk N–S shortening (Betts, Valenta and Finlay 2003) and an oblique ramp-thrust geometry between these two fault systems.

In the adjacent Coober Pedy Ridge region (Fig. 1), SHRIMP data on metamorphic zircon (Fanning, Reid and Teale 2007; Jagodzinski et al. 2007) and LA-ICPMS monazite ages (Payne et al. 2008) from intensely foliated mid-crustal granulites suggest that high-temperature conditions may have prevailed as early as 1590 Ma, extending to c. 1565 Ma, overlapping with the timing of deformation in the Mount Woods region.

In the southeastern Gawler Craton, early Mesoproterozoic NW–SE-directed compressional deformation is recorded in the Moonta–Wallaroo region, where the syndeformational metamorphic grade decreases from amphibolite- to greenschist-facies towards the NE (Conor 1995). Early Mesoprotoerozoic, c. 1580 Ma, retrograde shear zones are also locally developed within the NE-trending Kalinjala Mylonite Zone (Foster and Ehlers 1998; Hand, Reid and Jagodzinski 2007). Further east, within the Barossa Complex, LA-ICPMS metamorphic zircon and monazite ages from coarse-grained garnet–sillimanite migmatitic granulites in the Myponga Inlier indicate high-grade (750 °C, 5–6 kbar) metamorphism and deformation in the interval 1590–1580 Ma (Szpunar et al. 2007).

Regional-scale architecture of early Mesoproterozoic deformation

Viewed on a regional scale, the northwestward decrease in early Mesoproterozoic metamorphic grade from the Barossa Complex through the eastern Gawler Craton is reminiscent of a hinterland–foreland system (e.g. Stockmal et al. 1986; Allen and Homewood 1986). This pattern is typified by the formation of orogenic domains (hinterland) synchronous with the development of adjacent basin domains (foreland). Unlike extensional systems, the foreland basins tend to have broad shallow profiles, reflecting the flexural response associated with hinterland development. Furthermore, it appears that the regional variation of metamorphic grade for the Olarian Orogeny in the Curnamona Province shows a similar spatial organisation as shown above for the eastern Gawler Craton. Although we acknowledge there are considerable uncertainties regarding the timing of peak metamorphism in the Curnamona Province there is little doubt that compressional deformation occurred in the early Mesoproterozoic (Page et al. 2005; Rutherford, Hand and Barovich 2007). The overall metamorphic architecture of the region is such that granulite facies rocks of the Broken Hill region give way to progressively lower grade and less deformed rocks to the NW, culminating in the late synorogenic, undeformed rocks of the Benagerie Volcanics (Fig. 3), dated at 1581 ± 4 Ma (Fanning et al. 1998). This architecture is consistent with a foreland region to the NW.

In this analysis, a comparatively simple pattern of early Mesoproterozoic tectonism emerges within the southern Australian Proterozoic terranes that comprises a NE–SW-oriented domain occupied by the 1590–1580 Ma Gawler Range Volcanics – Benagerie Volcanics (GRV–BV), flanked by NE- to ENE-trending 1600–1570 Ma deformation belts (Fig. 4). Given the intensity of tectonism in these belts and the comparative lack of deformation in the upper crustal GRV–BV system, it is likely that bulk tectonic transports were directed toward the GRV–BV domain. The implication is that the GRV–BV is a synorogenic system located in a foreland position to the flanking, hinterland regions that underwent broadly NW–SE driven crustal thickening.

The Gawler Range Volcanics themselves are mostly undeformed (Blissett et al. 1993). However, in a typical foreland basin, synorogenic sediments would be expected to record some deformation. Within the southeastern Gawler Craton there is evidence for deformation within the Corunna Conglomerate (Fig 1). The lower conglomerate units are separated by unconformities that are

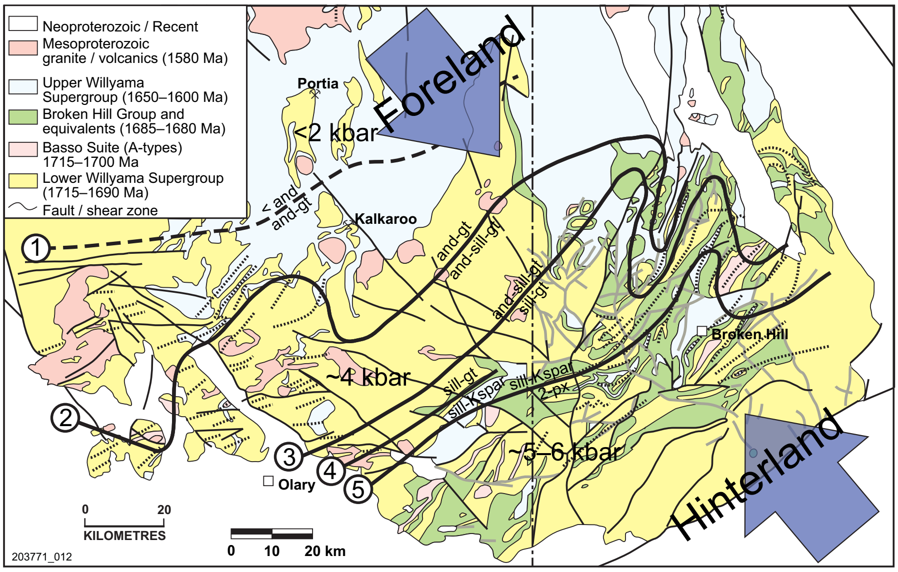

Figure 3 *Simplified map of the southeastern Curnamona Province showing the distribution of deformation and metamorphism associated with the 1600–1580 Ma Olarian Orogeny (Stevens 1986; Clarke et al. 1987; Laing 1996). The intensity of tectonism decreases toward the NW, suggesting the orogen may have had a NW–SE component of tectonic transport. The dotted lined show the axial trace of* D_2 *folds which have upright to reclined orientations and deform earlier low-angle large-scale folds that invert large areas of the stratigraphy. The numbered lines represent isograds of increasing metamorphic intensity. The c. 1580 Ma granites immediately postdate the penetrative deformation. (and = andalusite; gt = garnet; Kspar = K-feldspar; px = pyroxene; sill = sillimanite.)*

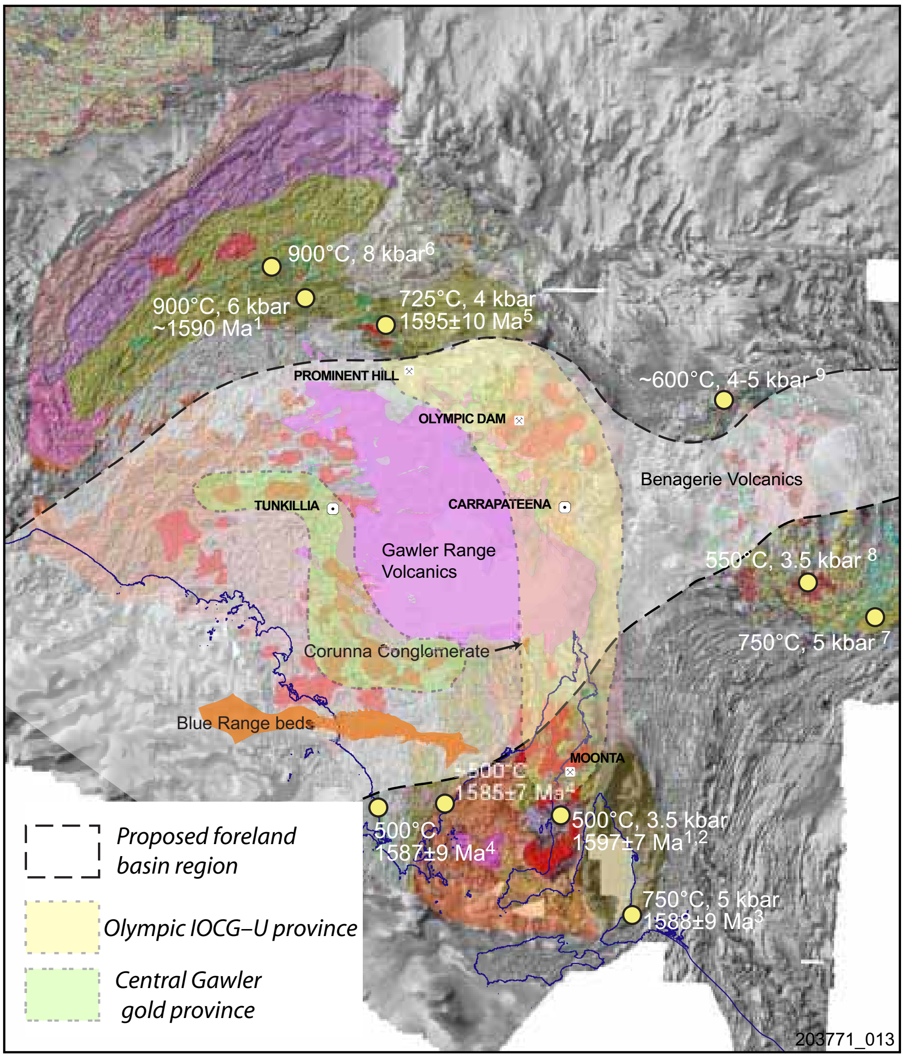

Figure 4 *Inferred early Mesoproterozoic NW–SE contractional tectonic system in southern Australian Proterozoic terranes with a synorogenic foreland region occupied by the Gawler Range and Benagerie Ridge volcanics flanked by regions of deformation. Locations identified are those for which quantitative or qualitative estimates for the temperature and pressure conditions of metamorphism are documented. Also shown are outlines of the Olympic IOCG–U and central Gawler gold provinces, the principal Mesoproterozoic mineral systems of the Gawler Craton. (Notes: 1 = Fanning, Reid and Teale 2007; 2 = Conor 1995; 3 = Szpunar et al. 2007; 4 = Foster and Ehlers 1998; 5 = Jagodzinski et al. 2007 and this study; 6 = K Cutts, University of Adelaide, unpublished data 2008; 7 = White et al. 2004; 8 = Clarke et al. 1987; 9 = Shafton 2006*

co-planar with the subsequent limb rotation within the overall folded sequence (Lemon 1972). This style of unconformable accumulation is typical of proximal foreland basins (e.g. Anadon et al. 1986; Jones 1991), where progressive titling of sequences occurs as deformation progresses forelandward with associated flexural loading. In the Baxter Hills (informally known as the Corunna Range), these folds are crosscut by Gawler Range Volcanics related porphyritic dykes (Lemon 1972; McAvaney and Reid 2008), providing a maximum age constraint on the deformation. We note however, that the age of deposition of the Corunna Conglomerate from the Baxter Hills region is poorly constrained. In this region, detrital zircon ages indicate the conglomerate was most likely derived from the Gawler Craton, however, the maximum depositional ages are c. 1740 Ma, which do not indicate deposition of the conglomerate was necessarily contemporaneous with the Gawler Range Volcanics (McAvaney and Reid 2008). However, a similar, but flat-lying sequence of conglomerates and clastic sediments are interlayered with 1585 ± 15 Ma tuffaceous units in the Roopena region (Johnson 1993). The interpreted stratigraphic correlation between the sediments in the Roopena and Corunna regions (Daly 1993; Parker and Fanning 1998) suggests that the sedimentation and deformation observed at the Baxter Hills may be synchronous with deformation in the proposed hinterland regions.

Other sedimentary packages may also be part of the same basin system. Although no geochronological constraints are yet available, conceivably the mildly folded Blue Range beds in central and western Eyre Peninsula may be part of the same synorogenic sedimentary/volcanic packages (Fig. 1). More direct evidence occurs in the Mount Painter region where recent zircon geochronology on Gawler Range Volcanics-aged and older detritus is consistent with derivation from the Gawler Craton in rocks deformed between c. 1590–1575 Ma (Fanning, Teale and Robertson 2003; Ogilvie 2006; Shafton 2006). This suggests that part of the (lower?) Gawler Range Volcanics may have been incorporated into and undergone uplift on the margins of the early Mesoproterozoic deformation belts. Furthermore, the deformation in the Mount Painter region in the interval c. 1590–1575 Ma (Shafton 2006; Ogilive 2006) suggests that some of the synorogenic sequences may have been subsequently deformed within the early Mesoproterozoic orogenic system.

Geodynamic setting of early Mesoproterozoic, Hiltaba-related mineral systems

The bulk of early Mesoproterozoic mineral systems in the Gawler Craton appear to have developed in the proposed foreland region (Fig. 5). The existence of a NW–SE compressional regime suggests that NW–SE-directed fault systems would have likely formed or been reactivated with strike–slip movement, leading to the development of dilatant zones at fault bends along these corridors. Intersection of these faults with contractional NE–SW-oriented structures that may have been zones of fluid expulsion would provide possible zones of fluid flow focus (see also Direen and Lyons 2007; Hand, Reid and Jagodzinski 2007).

The broader geodynamic setting of the early Mesoproterozoic tectonism in the southern Australian Proterozoic terranes is not well constrained. The timing of deformation is broadly coincident with arc-related magmatism recorded in the Musgrave Province (Wade, Barovich and Hand 2006) and widespread intracratonic reworking in response to approximate N–S shortening in the North Australian Craton (Hand and Buick 2001). However, it is unclear whether the thermal driver for the Hiltaba system is a consequence of: (1) the prevailing lithospheric regime; or (2) is imposed upon it. For scenario 1, one possibility is that the precursor setting of early Mesoproterozoic tectonism was a continental back arc, with the high-temperature regime that drove Hiltaba magmatism and the high-geothermal gradient metamorphism in the c. 1600–1580 Ma orogenic belts inherited from a thinned lithosphere. In this case, compressional deformation would probably have been driven by collision or accretion at a mechanically connected margin. Scenario 2 could simply reflect the thermal consequences of a plume (Betts et al. 2007) whose initiation and location may not be related to the synchronous deformation in the lithosphere. Irrespective, in terms of the development of the early Mesoproterozoic mineral systems, there appears to have been a major difference in the nature of the lithosphere that gave rise to the contrasting IOCG–U and Au-dominated systems (Hand, Reid and Jagodzinski 2007). The IOCG–U systems in the eastern Gawler Craton developed within lithosphere characterised by higher contemporary heat flow than the Au-dominated systems to the west. It is unlikely that this difference in heat flow is a consequence of the mineral system development. Rather it reflects major average differences in lithospheric composition, suggesting that the eastern Gawler Craton may contain a pre- or early-Mesoproterozoic boundary between contrasting lithospheric domains (Howard et al. 2006) that exerted a first order control on the subsequent distribution of the IOCG–U and Au-dominated mineral systems.

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