Contrasting styles of Proterozoic crustal evolution: A hot-plate tectonic model for Australian terranes

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ABSTRACT

Proterozoic terranes in Australia record complex tectonic histories in the interval 1900–1400 Ma that have previously been interpreted by means of simple intracratonic or plate-tectonic models. However, these models do not fully account for (1) repeated tectonic reactivation (both orogenesis and rifting), (2) mainly high-temperature–low-pressure metamorphism, (3) rifting and sag creating thick sedimentary basins, (4) the nature and timing of voluminous felsic magmatism, (5) relatively large aspect ratio orogenic belts, and (6) a general paucity of diagnostic plate-boundary features. A key to understanding these histories is the observation that Australian Proterozoic terranes are characterized by an extraordinary, but heterogeneous, enrichment of the heat-producing elements. This enrichment must contribute to long-term lithospheric weakening, and thus we advocate a hybrid lithospheric evolution model with two tectonic switches: plate-boundary–derived stresses and heat-producing-element–related lithospheric weakening. The Australian Proterozoic crustal growth record is therefore a function of the magnitude of these stresses, the way in which the heat-producing elements are distributed, and how both of these change with time.

Keywords: heat sources, plate tectonics, rheology, differentiation.

INTRODUCTION

The popularity of uniformitarian principles has meant that most contemporary views of Proterozoic crustal growth have been framed in terms of modern-style plate tectonics. These models appear appropriate in many cases, including the Paleoproterozoic–Mesoproterozoic evolution of North America (Hoffman, 1989) and the evolution of those Mesoproterozoic terranes related to the assembly of Rodinia, including those in Australia (Myers et al., 1996). However, for the Paleoproterozoic–Mesoproterozoic evolution of Australian terranes, there is less consensus, and two end-member models have been proposed.

Early work advocated an intraplate, asthenosphere-driven model for lithospheric evolution in which vertical, rather than lateral, accretion was dominant (Etheridge et al., 1987). More recently, plate-tectonic models have become popular, based largely on evidence from the Halls Creek orogen, where a clear case exists for the collision of the Kimberley craton and the proto–North Australian craton (Sheppard et al., 2001) during the Paleoproterozoic (1870–1820 Ma); and on the presence of apparent subduction-related igneous rocks in central Australia (Zhao and McCulloch, 1995). Giles et al. (2002) used these observations to propose a hybrid plate-tectonic, asthenosphere-driven model.

There are a number of observations, however, that remain poorly explained by these models, and we advocate a more general approach to understanding Proterozoic crustal evolution. This is based on the recognition of key geological observations, as well as an understanding of the chemical and physical properties of the lithosphere. A fundamental tenet of any model for lithospheric behavior is that tectonic activity is modulated by (1) variations in far-field stresses, and (2) temporal and spatial variations in lithospheric strength. The latter is controlled by strain rate, fluid activity, and thermal regime, including crustal heat production, mantle heat flow, thermal conductivity, and any heating via advection. In the modern Earth the continental lithosphere is strong in relation to imposed tectonic loads and acts largely as a stress guide. It will not deform unless far-field stresses are significantly amplified (as in some plate-margin settings) or if the crust is sufficiently weak. We suggest that tectonic switches relating to lithosphere strength and far-field stresses are critical in controlling the evolution of Australian Proterozoic terranes. This notion of an extra tectonic switch helps explain many of the enigmatic features of Australian Proterozoic crustal growth within a global plate-tectonic scenario.

AUSTRALIAN PROTEROZOIC CRUSTAL EVOLUTION

As noted by many, several distinctive features characterize the majority of Australian Proterozoic terranes (Wyborn et al., 1992; Betts et al., 2002). Different emphases placed on these features have tended to polarize interpretation into radically differing tectonic scenarios (Etheridge et al., 1987; Myers et al., 1996). These features include repeated tectonic reactivation involving both orogenesis (compressional deformation) and rifting (extensional deformation accompanied by mafic and felsic volcanism, and with broadly contemporaneous granite magmatism) and quasi-continuous bimodal magmatism with only rare intermediate compositions. Mafic magmatism is almost exclusively related to periods of crustal extension. Epsilon neodymium values point toward largely crustal sources for most Australian felsic igneous rocks (Wyborn et al., 1992), with relatively limited mantle input. Wyborn et al. (1992) also recognized a broad division of felsic igneous rocks between (A) predominant and temporally widespread Sr-depleted, Y-undepleted granites and (B) rare Sr-undepleted, Y-depleted granites. The geochemical signature of type A granites is unlike

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TABLE 1. HEAT FLOW, HEAT PRODUCTION, AND METAMORPHIC PRESSURES IN AUSTRALIAN PROTEROZOIC TERRANES

Terrane	Average metamorphic pressure (kbar)	Average surface heat flow (mWm^{-2})	Total area of outcrop (km^2)	U (ppm)	Th (ppm)	K (wt%)	Q (μWm^{-3})
Arunta inlier	6–9 (central) 4–5 (south/north)	59	27,233	7.2	40.1	4.46	5.24
Willyama inliers	4–6	72	1920	4.5	20.2	2.44	2.88
Eastern Gawler craton	5–7	94	20,888	7.4	32.8	4.94	4.79
Georgetown inlier	3–5	89	6411	9.4	29.1	4.93	5.06
Halls Creek	3.5–5	66	12,073	4.8	20.2	4.26	3.15
Mount Isa inlier	∼4	83	10,935	7.2	33.9	4.93	4.82
Mount Painter Province	3–4	N.D.	411	29	110	4.62	16.13
Musgrave inlier	6–7	N.D.	5499	1.3	21.8	4.19	2.68
Pine Creek inlier	3–5	83	8626	7.5	32.1	4.55	4.73
Tanami inlier	∼3.5	N.D.	790	11.7	30.7	5.19	5.79
Tennant Creek inlier	3–4	96	4131	6.1	25.2	4.84	3.89
Total		82.6 ± 17.7	100,477	6.8	32.1	4.62	4.6
	1650–1480 Ma *(79)*		37,328	8.6	35.6	4.83	5.3
	1800–1650 Ma *(117)*		23,565	6.7	38.4	4.58	5.0
	1850–1800 Ma *(94)*		13,788	7.0	28.8	4.68	4.4
	Pre 1850 Ma *(70)*		19,612	4.8	22.0	4.31	3.3

Note: Heat production is that of the modern day, based on present abundances of the heat-producing elements, as shown. Raw data from Budd et al. (2001). Heat flow data from Cull (1982). Only good-quality data are included. N.D. = no data available. Total and average values include all rocks for which age and heat-production data are available. Italicized numbers in parentheses indicate number of map-scale units used.

those of modern subduction or collisional settings or those typical of Archean terranes. Strontium depletion implies derivation from shallow sources where plagioclase, rather than garnet, was stable (Singh and Johannes, 1996). Another feature is long-lived extensional tectonism involving rift-related sedimentation and mafic volcanism, with associated and/or subsequent felsic volcanism. Granite magmatism generally occurs during the early stages of rifting, either accompanying the mafic volcanism or immediately postdating it. Following rifting, thick, mainly marine sedimentary sequences accumulated, centered on the rift basins but with wide areal extent. These periods of sediment accumulation via sag may be punctuated by granite magmatism and felsic volcanism (Page et al., 2000), highlighting the unusual nature of crustal evolution at this time. Many of the orogens involved high-temperature–low-pressure metamorphism (Table 1); these events often appear to be long-lived (Williams et al., 1996) and unrelated to magmatism (Connors and Page, 1995). This style of orogeny involving little crustal thickening and a hot lithosphere is quite different from the modern-day style of continental collision characterized by substantial crustal thickening, and clockwise pressure-temperature-time paths. High-pressure, intermediate- to low-temperature metamorphic belts are absent. Another feature includes the absence of sutures and only rare occurrence of the type B granites with plate-margin affinities and geochemical signatures not unlike Phanerozoic adakitic granites (Sheppard et al., 2001). We note that the understanding of the tectonic setting as plate boundary hinges primarily on interpretation of the felsic igneous rocks. Zhao and McCulloch (1995) and others used the occurrence of type B granites to argue for subduction-related processes at Proterozoic plate-boundary zones. However, these type B granites make up only 3.8% of all Australian Proterozoic felsic igneous rocks, and the majority of these are in the Halls Creek orogen (77%) and the Arunta inlier (22%) (Budd et al., 2001). The last feature includes generally low aspect ratio orogenic architectures, unlike many modern curvilinear plate-boundary belts (Fig. 1), although subsequent tectonic disruption may have accentuated this feature.

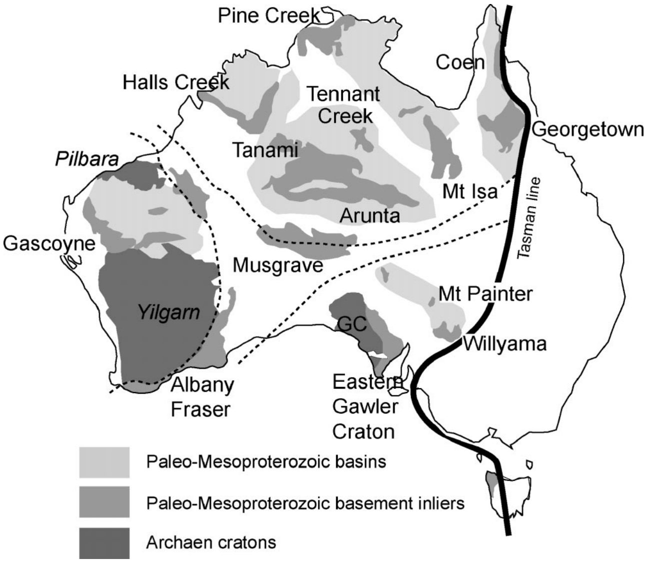

Figure 1. Location of major Australian Proterozoic terranes. Largely Archean and Phanerozoic rocks form west and east of continent, respectively. Deformed and metamorphosed basement inliers (named) are shown together with approximate extent of major Proterozoic sedimentary basins ranging in age from 2200 Ma to 1100 Ma. Dashed line indicates inferred extent of structures associated with assembly of Rodinia (1400–1100 Ma).

As recognized by most recent studies (e.g., Betts et al., 2002), many of the preceding observations point to a rather diffuse style of tectonics in which the role of plate-boundary forcing is obscured by processes that tend to smear out the tectonic response in space and time. A key to understanding this lies in the observations that point to elevated thermal regimes (crustal derived magmatism and high-temperature–low-pressure metamorphism). In the following we link these ideas, introducing the notion of a new tectonic switch modulated by coupled changes in lithospheric thermal regimes and strength.

LITHOSPHERIC THERMAL REGIME

In establishing a model for crustal evolution, one of our primary concerns is lithospheric thermal structure. As noted by Davies (1993, p. 281), ‘‘the tectonic modes operating at any given time in the Earth are ultimately related to the thermal evolution, since tectonics is driven by heat removal from the Earth's interior.'' In lithospheric dynamics, heat-production distribution plays a crucial role in the strength distribution (Sandiford and McLaren, 2002). One of the most outstanding features of Australian Proterozoic terranes is their high surface heat flow (Cull, 1982). Available measurements average 83 ± 18 mWm^{-2}, well in excess of the 49–54 mWm^{-2} Proterozoic global average (Morgan, 1984). Seismic evidence for relatively cool mantle (Goes et al., 2000), together with the lack of evidence for thermal transients, suggests that anomalous heat flow reflects crustal radiogenic sources that contribute 50–60 mWm^{-2}, and up to 70 mWm^{-2} in some cases (McLaren et al., 2003).

Much of this heat-producing element enrichment is contained within felsic igneous rocks in the upper 5–10 km of the crust. When normalized by area of outcrop, Australian Proterozoic felsic igneous rocks give a present-day average heat production of 4.6 μWm^{-3} (Table 1; McLaren et al., 2003). This value is twice that of average granite, and although extreme, appears to be a primary feature, as the rocks have low Th/U ratios and uranium and thorium are largely within primary accessory

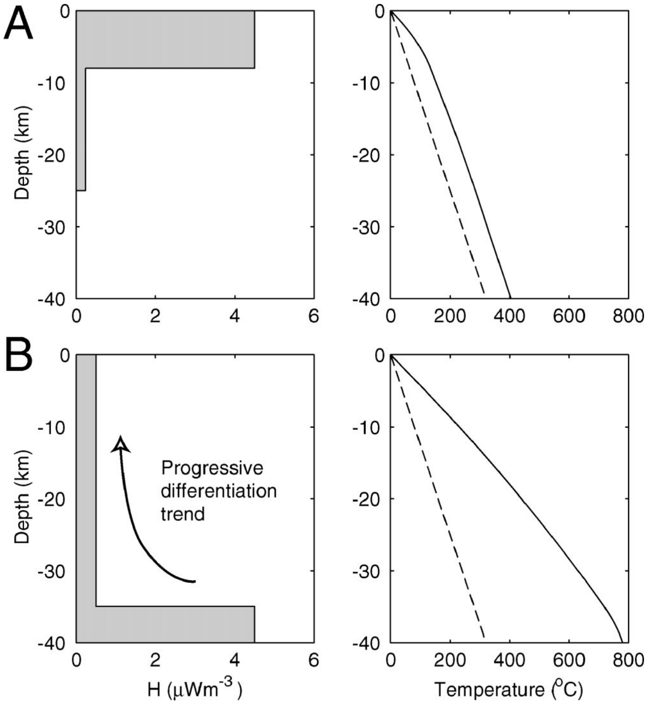

Figure 2. Crustal heat-producing-element distributions and resultant geotherm for (A) highly differentiated heat-production distributions where majority of crustal heat sources are located in uppermost crust (this configuration is appropriate for modern-day crust in many Australian terranes), and (B) undifferentiated heat-production distributions where majority of crustal heat sources are located in lower crust; appropriate for Early Proterozoic crust in many Australian terranes. Dashed line indicates geotherm that would apply in crust containing no heat-producing elements (i.e., mantle contribution). Differentiation of crustal heat sources from distribution (A) to distribution (B) through tectonic processing (particularly magmatism) affects significant increase in crustal strength and is responsible for progressive cratonization of Australian terranes through Paleoproterozoic–Mesoproterozoic. Both distributions give total crustal contribution to surface heat flow of 40 mWm^{-2}.

phases. We also note trends in heat production with age. Younger granites are generally more enriched in heat-producing elements than older granites (Data Repository Table DR1).[1] That these younger granites also generally have more negative εNd values (Wyborn et al., 1992) suggests progressive enrichment over time.

During the Proterozoic, the contribution of these heat sources is likely to have been higher, as decay of the heat-producing elements results in a significant decrease in heat production (~20%–30% for typical granitic compositions) over the appropriate time intervals. Consequently, many parts of the Australian Proterozoic crust may have contributed 60–85 mWm^{-2} to the surface heat flow—two to three times the present-day continental average. We also note that the Australian average includes significant variability between terranes (Table 1). Terranes with higher-pressure metamorphism (such as the Musgrave inlier) or where the average age of orogenesis is older (such as Halls Creek) are characterized by lower average heat production than those terranes where crustal activity continued over long intervals (such as Mount Isa). Thus, heat-production enrichment is apparently correlated with the longevity and nature of the tectonic activity.

The extreme heat-producing element enrichment that characterizes Australian Proterozoic terranes must have contributed to significant long-term lithospheric weakening (e.g., Goffe et al., 2003). This effect is most pronounced when the heat sources are concentrated in the deep crust rather than in the upper crust (Fig. 2), and will change as the heat source distribution is modified by tectonic activity. We suggest that this thermomechanical feedback system provided an important switch for tectonic activity in Australian terranes.

TOWARD AN INTEGRATED MODEL FOR LITHOSPHERE EVOLUTION

Continental crust will deform at a rate dictated by the ratio of the applied stress and the lithosphere strength averaged over an appropriate length scale. Radiogenic heat sources give rise to significant lithospheric weakening, and thus the abundance and redistribution of crustal heat sources should have exerted profound control on tectonic activity in areas of high average heat production. This view of tectonic activity in terms of the long-term thermomechanical stability of the crust has proven useful in understanding the distribution of active deformation in modern continental interiors, such as central Asia (Neil and Houseman, 1997).

Available isotopic data (Wyborn et al., 1992) suggest that Australian Proterozoic granites are largely the product of recycling of earliest Proterozoic crust, meaning that the Early Proterozoic lithosphere was characterized by intermediate to high concentrations of heat-producing elements at deeper crustal levels. This configuration would have greatly increased lower crustal thermal regimes and means that the Australian Proterozoic lithosphere was significantly weaker than the modern lithosphere. For example, for a mantle heat flow of 20 mWm^{-2}, if heat sources that contribute 80 mWm^{-2} to the surface heat flow had been concentrated in the deep crust, Moho temperatures would have been ~900 °C, meaning that the lithosphere was <100 km thick and weakened by a factor of at least 2–3 when compared with low-heat-production crust, or where heat sources were in the upper crust (Sandiford and McLaren, 2002). This observation implies very real differences in the thermal and mechanical behavior of early Australian Proterozoic crust when compared with modern lithosphere. By virtue of its inherent weakness, the Australian Proterozoic crust must have been sensitive to even mild applied forces.

Sandiford and McLaren (2002) showed that the progressive redistribution of heat sources into the upper crust through tectonic processing leads to a long-term increase in lithospheric strength. This effect is most pronounced for the generation and emplacement of felsic igneous rocks. We suggest that the progressive redistribution of heat-producing elements through tectonic processing represents a transition between soft-plate deformation that persisted throughout many regions of Australian crust during the Paleoproterozoic–Mesoproterozoic, and the modern style, where this crust appears to be rigid and cratonlike and where deformation occurs principally in plate-boundary zones. The corollary of this model is that the onset of rigid plate behavior was probably diachronous, with cooler, lower-heat-production terranes, including Halls Creek, achieving a stable cratonlike state earlier than higher-heat-producing terranes.

Crust so enriched in the heat-producing elements would be unlikely to support significant thickening, and we suggest that the characteristic low-pressure style of metamorphism reflects the primary tectonic mode, with the exposed structural level of the crust after long-term erosion being relatively shallow. This implies a feedback for the preservation of heat-production anomalies: the higher the total heat production, the weaker the lithosphere, the less the crustal thickening, and the less the resulting erosion. Consequently, a high proportion of the initial heat production is preserved in the upper crust, rather than being eroded and dispersed. Preservation of high

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[1] GSA Data Repository item 2005125, Tables DR1–DR15, heat-production data, Australian Proterozoic felsic igneous rocks, is available online at www.geosociety.org/pubs/ft2005.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301-9140, USA.

concentrations of heat-producing elements in the uppermost crust allows the possibility of subsequent tectonic reactivation and/or metamorphism as a consequence of burial beneath later sedimentary cover.

The hot lithosphere, high geothermal gradient regime, and lack of significant crustal overthickening help to account for the geochemical signatures of the granites, with the characteristic Sr-depleted, Y-undepleted granites produced in a lower crust in which garnet is not a residual phase. Plutons with crustal adakitic affinity would be formed only where the crust was thick enough for the granite source to have residual garnet or where subduction occurred. This is more likely for cooler, stronger, lower-heat-production crust. Halls Creek is the best example of such cool crust and hosts the majority of type B granite occurrences.

Observed temporal correlations between terranes are likely to reflect tectonic forcing related to far-field stress variations as a consequence of plate-boundary processes. Any terrane would be expected to respond to the far-field stresses if the distribution of heat sources was sufficient to thermally weaken the lithosphere. The far-field stresses may be compressive or extensional, leading to orogeny or sedimentary basin activity.

Thus, we advocate a lithospheric evolution model with two tectonic switches: (1) plate-boundary–derived stresses and (2) heat-producing-element–related lithospheric weakening. Recognition of long-term lithospheric weakening as a result of heat-producing element enrichment provides a key insight into tectonic activity in Australian terranes.

DISCUSSION

Whether the behavior that characterizes Australian terranes occurred elsewhere is still to be resolved. High-heat–producing granites are known from southern India (Roy and Rao, 2000), Scandinavia (Wilson and Åkerblom, 1982), and the Canadian Cordillera (Hyndman and Lewis, 1995), but in these regions the heat-producing-element enrichment is less extreme and enriched granites are a minor component of their terranes.

If we accept the notion that the scale of the enrichment in Australia is unique, we are faced with the question of the origin of the anomaly. This remains an outstanding problem. Available geochemistry (Table 1) suggests that the enrichment is heterogeneous, and we suggest that these variations reflect heterogeneities in the enriched Early Proterozoic mantle lithosphere from which the crustal melts were sourced. Because regions without significant heat-production enrichment would have been more stable than those with a high concentration of heat sources, it is also possible that the current distribution of Proterozoic inliers maps the distribution of anomalous heat sources in the early lithosphere. This may provide fundamental data on the length scale of heat-producing-element enrichment. We suggest that this enriched material may have been added to the lithosphere system during a massive mantle overturn event (e.g., Davies, 1995). The extreme enrichment of the Australian lithosphere was probably fortuitous, but the presence of high-heat-producing granites in other terranes may suggest that enriched material was also sampled elsewhere.

The long-term strengthening trend that results from the redistribution of the heat-producing elements from the lower crust to the upper crust through tectonic processing may reflect a fundamental control on the chemical organization of the continents. Thus, the history of tectonic activity in high-heat-producing-element–enriched terranes in Australia may represent an example of the transition between soft-plate early Earth tectonics (e.g., Kröner, 1991) and rigid-plate modern Earth tectonics.

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REFERENCES CITED

Betts, P.G., Giles, D., Lister, G.S., and Frick, L.R., 2002, Evolution of the Australian lithosphere: Australian Journal of Earth Sciences, v. 49, p. 661–695.

Budd, A.R., Wyborn, L.A.I., and Bastrakova, I.V., 2001, The metallogenic potential of Australian Proterozoic granites: Geoscience Australia, Record 2001/12.

Connors, K.A., and Page, R.W., 1995, Relationships between magmatism and deformation in the western Mount Isa Inlier, Australia: Precambrian Research, v. 71, p. 131–153.

Cull, J.P., 1982, An appraisal of Australian heat-flow data: Bureau of Mineral Resources, Journal of Australian Geology and Geophysics, v. 7, p. 11–21.

Davies, G.F., 1993, Conjectures on the thermal and tectonic evolution of the Earth: Lithos, v. 30, p. 281–289, doi: 10.1016/0024-4937(93)90041-A.

Davies, G.F., 1995, Punctuated tectonic evolution of the Earth: Earth and Planetary Science Letters, v. 136, p. 363–379.

Etheridge, M.A., Rutland, R.W.R., and Wyborn, L.A.I., 1987, Orogenesis and tectonic process in the Early to Middle Proterozoic of northern Australia, *in* Kroner, A., ed., Precambrian lithospheric evolution: American Geophysical Union Geodynamic Series 17, p. 131–147.

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

Goes, S., Govers, R., and Vacher, P., 2000, Shallow mantle temperatures under Europe from P and S wave tomography: Journal of Geophysical Research, v. 105, p. 11,153–11,169.

Goffe, B., Bousquet, R., Henry, P., and Le Pichon, X., 2003, Effect of the chemical composition of the crust on the metamorphic evolution of orogenic wedges: Journal of Metamorphic Geology, v. 21, p. 123–141.

Hoffman, P.F., 1989, Speculations on Laurentia's first gigayear (2.0 to 1.0 Ga): Geology, v. 17, p. 135–138.

Hyndman, R.D., and Lewis, T.J., 1995, The thermal regime along the southern Canadian Cordillera Lithoprobe corridor: Canadian Journal of Earth Sciences, v. 32, p. 1611–1617.

Kröner, A., 1991, Tectonic evolution in the Archean and Proterozoic: Tectonophysics, v. 187, p. 393–410.

McLaren, S., Sandiford, M., Hand, M., Neumann, N., Wyborn, L., and Bastrakova, I., 2003, The hot southern continent: Heat flow and heat production in Australian Proterozoic terranes: Geological Society of America Special Paper 372, p. 157–167.

Morgan, P., 1984, The thermal structure and thermal evolution of the continental lithosphere: Physics and Chemistry of the Earth, v. 15, p. 107–185.

Myers, J.S., Shaw, R.D., and Tyler, I.M., 1996, Tectonic evolution of Proterozoic Australia: Tectonics, v. 15, p. 1431–1446.

Neil, E.A., and Houseman, G.A., 1997, Geodynamics of the Tarim Basin and the Tian Shan in central Asia: Tectonics, v. 16, p. 571–584.

Page, R.W., Jackson, M.J., and Krassay, A.A., 2000, Constraining sequence stratigraphy in northern Australian basins; SHRIMP U-Pb zircon geochronology between Mt. Isa and McArthur River: Australian Journal of Earth Sciences, v. 47, p. 431–459.

Roy, S., and Rao, R.U.M., 2000, Heat flow in the Indian shield: Journal of Geophysical Research, v. 105, p. 25,587–25,604.

Sandiford, M., and McLaren, S., 2002, Tectonic feedback and the ordering of heat-producing elements within the continental lithosphere: Earth and Planetary Science Letters, v. 204, p. 133–150.

Sheppard, S., Griffin, T.J., Tyler, I.M., and Page, R.W., 2001, High- and low-K granites and adakites at a Palaeoproterozoic plate boundary in northwestern Australia: Geological Society [London] Journal, v. 158, p. 547–560.

Singh, J., and Johannes, W., 1996, Dehydration melting of tonalites; part II, Composition of melts and solids: Contributions to Mineralogy and Petrology, v. 125, p. 26–44.

Williams, I.S., Buick, I.S., and Cartwright, I., 1996, An extended episode of early Mesoproterozoic metamorphic fluid flow in the Reynolds Range, central Australia: Journal of Metamorphic Geology, v. 14, p. 29–47.

Wilson, M.R., and Åkerblom, G.V., 1982, Geological setting and geochemistry of uranium-rich granites in the Proterozoic of Sweden: Mineralogical Magazine, v. 46, p. 233–245.

Wyborn, L.A.I., Wyborn, D., Warren, R.G., and Drummond, B.J., 1992, Proterozoic granite types in Australia: Implications for lower crust composition, structure and evolution: Royal Society of Edinburgh Transactions, Earth Sciences, v. 83, p. 201–209.

Zhao, J-X., and McCulloch, M.T., 1995, Geochemical and Nd isotopic systematics of granites from the Arunta Inlier, central Australia: Implications for Proterozoic crustal evolution: Precambrian Research, v. 71, p. 265–299.

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