Some thermal consequences of high heat production in the Australian Proterozoic

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The role of radiogenic decay in generating high-temperature thermal regimes in near-normal-thickness crust has been largely ignored. This oversight reflects a perception that radiogenic-heat-production concentrations are generally too low to generate significantly elevated conductive thermal regimes. However, in parts of the Australian Proterozoic, crustal (radiogenic) heat production that is largely concentrated in granites is roughly twice the world average for Proterozoic terranes. The existence of these anomalous heat-production concentrations in Australian Proterozoic rocks has important implications for generating high geothermal gradient regimes without appealing to external heat sources. The source region for most of these anomalously radiogenic granites was a lower crustal layer that was underplated from the mantle before 2000 Ma. Why this mantle event was so unusually enriched in K, Th, and U at this period of crustal evolution remains enigmatic.

Heat production in some Australian Proterozoic terrains

High-geothermal-gradient processes dominate the geological record in the Australian Proterozoic. These are principally expressed in the formation of regional high-temperature low-pressure metamorphic terrains (e.g., Mount Isa Inlier, northern Arunta Inlier, Broken Hill Block) and voluminous, crustally derived granitic magmatism. Considerable worldwide effort has been directed toward the study of high-geothermal-gradient regimes, principally because they are thought to represent significant departures from general notions of normal continental thermal conditions. For this reason, the advection of heat in the form of magmas is generally considered necessary to create a high-temperature regime in near-normal-thickness crust. While the advection of heat is likely to remain the governing paradigm for driving high-temperature low-pressure processes, the volume of synmetamorphic magmatism in some Australian high-temperature low-pressure metamorphic terrains (e.g., Broken Hill Block) appears too small to explain the observed metamorphism. Moreover, the application of the existing paradigm is challenged by several important observations:

- regional high-temperature low-pressure metamorphism comprehensively postdates (>120 Ma) voluminous magmatism in the northern Arunta and western Mount Isa Inliers (Williams et al. 1996: Journal of Metamorphic Geology, 14, 29–47; Conners & Page 1995 Precambrian Research, 71, 131–153.);
- in the northern Arunta Inlier, high temperatures (>650°C) and low pressures (500 MPa) persisted for upwards of 25 Ma (Williams et al., 1996: op. cit.), far in excess of that expected for heating from a primary magmatic source, and imply that metamorphism occurred in quasiconductive equilibrium; and
- many of the voluminous Palaeo- and Mesoproterozoic granitic magmas derived from moderately shallow crustal sources do not appear to be associated with major mantle-derived magmatic events (Wyborn et al. 1998: in AGSO Record 1998/33, 47–59).

Despite the spatial association between granitic bodies and high-temperature low-pressure metamorphism in both the Mount Isa and northern Arunta Inliers, the interval between metamorphism and granite intrusion precludes advection as the primary heating mechanism. A notable feature of these terranes is that the heat-production capacity of premetamorphic granites is much higher (6–16 $\mu W\ m^{-3}$) than average for the crust. In the northern Arunta Inlier for example, granites with an average heat-production capacity of ~7 $\mu W\ m^{-3}$ crop out over at least 1200 km^2 (Fig. 21A) and form sill-like bodies up to 4 km thick, representing a depth-integrated heat flow of 20–25 $mW\ m^{-2}$. The generally high surface heat flows that characterise Australian Proterozoic terranes (average ~80 $mW\ m^{-2}$; Cull 1982: BMR Journal of Australian Geology & Geophysics, 7, 11–21), coupled with the moderately thick mantle lithosphere (Zielhuis & van der Hilst 1996: Geophysical Journal International, 127, 1–16), suggest that the Australian Proterozoic crust generally contributes >50 $mW\ m^{-2}$ to the total surface heat flow (see also Taylor & McLennan 1985: table 5.5 in 'The continental crust: its composition and evolution', Blackwell Scientific Publications, Melbourne), and up to 80 $mW\ m^{-2}$ in places such as the northern Flinders Ranges. These values are well in excess of the estimated normal crustal contribution to surface heat flow — <30 $mW\ m^{-2}$ (Taylor & McLennan 1985: op. cit.).

Heat-production concentrations of the magnitude of those in parts of the Australian Proterozoic have profound implications for mid-crustal thermal regimes. In a modelled steady-state thermal regime for a crustal section in the northern Arunta Inlier (Fig. 21B), an insulating sedimentary layer a few kilometres thick with a thermal conductivity of 2.25 $W\ m^{-1}\ K^{-1}$ caps the bulk of the crust, which has an assumed thermal conductivity of 3 $W\ m^{-1}\ K^{-1}$ and heat production linearly decreasing from a maximum of 3 $\mu W\ m^{-3}$ at the surface to 0.5 $\mu W\ m^{-3}$ at the Moho. Applying a basal heat flow of 20 $mW\ m^{-2}$ results in a maximum surface heat flow of around 110 $mW\ m^{-2}$, dropping to around 90 $mW\ m^{-2}$ in areas of lower heat production. Although these values are high, they are still within the present-day range observed in Proterozoic regions such as the Mount Painter and Tennant Creek Inliers (Cull 1982: op. cit.).

At a depth of 18 km, roughly coinciding with the level of denudation in the southeast Reynolds and Anmatjira Ranges, the maximum heat flow is around 65 $mW\ m^{-2}$. For the heat-production distribution shown in Figure 21A, steady-state temperatures are up to 720°C at 18 km depth. This compares with regional peak metamorphic temperatures at 1580 Ma in the order of 680–750°C at around 18 km depth in the southeastern Reynolds and Anmatjira Ranges and along the Yalarimbi Range. These results suggest that the prolonged high geothermal gradient regime in the Reynolds Range (Williams et al. 1996: op. cit.) may have been largely generated by elevated levels of crustal heat production.

An important aspect of the thermal structure is the large vertical temperature gradients (up to 40°C km^{-1}) above the anomalous mid-crustal heat production. These large gradients reflect the extreme sensitivity of the thermal structure to the depth of burial of the heat-production layer. Additionally, they imply that moderately small differences in the depth of denudation across a terrain will be reflected by large regional temperature gradients.

The magnitude of potential lower-crustal temperatures is strongly dependent on the thermal properties of the crust. In particular, the thermal conductivity of a sedimentary layer blanketing the crust will have an important impact on lower-crustal temperatures. The average thermal conductivity estimate for sedimentary rocks in the Mount Isa region, for example, weighted according to stratigraphic thickness of the component sequences is ~2.6 W m^{-1} K^{-1} (MacLaren et al., submitted to Geology). The figure we chose (2.25 W m^{-1} K^{-1}; Fig. 21B) is based on the general results of conduc-

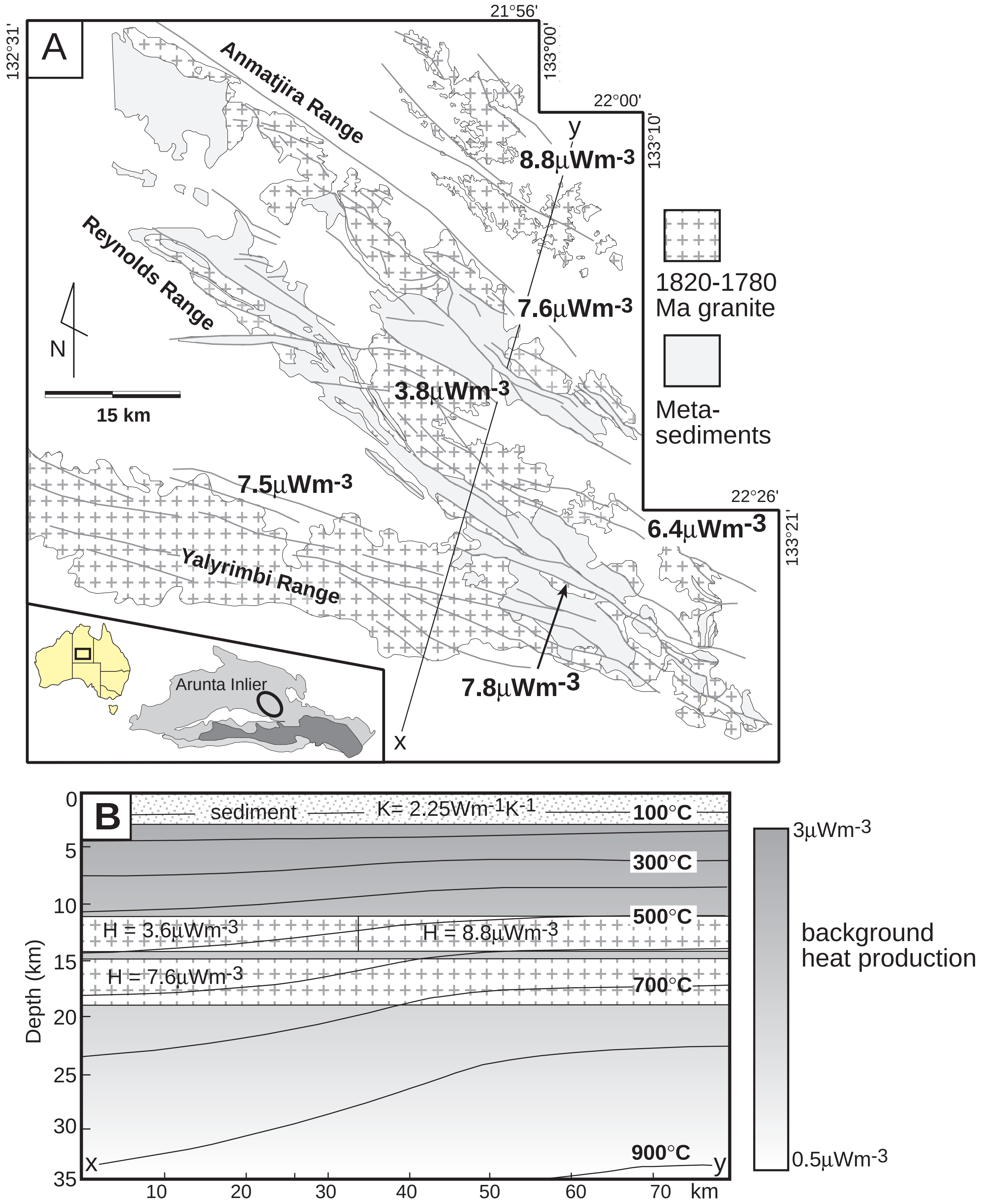

Fig. 21. (A) Distribution of high-heat-production granites in the Napperby region of the northern Arunta Inlier. (B) Steady-state thermal regime arising from burial of the anomalous heat production contained in the granites. This section approximates the pre-orogenic geometry based on field observations, including the movement of specific fault-blocks and the regional northward tilt. The heat production values are calculated for 1600 Ma, which roughly coincides with regional high-temperature low-pressure metamorphism.

tivity measurements. Increasing it by 25 per cent (to 2.8 W m^{-1} K^{-1}) would result in a ~40°C decrease in calculated Moho temperature. Even so, the thermal conductivity of partly consolidated and diagenetic sediments may be 25–50 per cent less than their lithified equivalents (e.g., Griffiths et al. 1992: in 'Geological applications to wireline logs II', Geological Society, Special Publication 65, 299–315). Therefore, the average thermal conductivity of blanketing sedimentary layers may be much lower (≤2.0 W m^{-1} K^{-1}). This suggests that the presence of sedimentary basins in crust with anomalous heat production may exert an important control on the generation of high-geothermal-gradient regimes.

Implications for granite genesis

Since the thermal regime is sensitive to the depth of burial of anomalous heat production, restoring the heat-production content of the mid-crustal granites to likely pre-segregation depths should logically lead to lower-crustal temperatures exceeding the granitic solidus. This suggests that some granite formation may be largely the crustal response to conductive thermal regimes generated by deeply buried heat production. If heat-production concentrations of the order calculated for the northern Arunta Inlier were located near the base of crust greater than ~30–35 km thick, lower-crustal temperatures would exceed the bulk crustal liquidus. This would have profound mechanical consequences for Proterozoic tectonism (e.g., crustal convection). That these processes do not appear to have occurred to any great extent suggests that, in places such as the Arunta Inlier, the Proterozoic crust was moderately thin. This in turn implies that the voluminous granites that characterise many Australian Proterozoic regions were sourced from shallow depths (~35 km; Johannes & Holz 1996: 'Petrogenesis and experimental petrology of granitic rocks', Springer-Verlag, Berlin), an inference consistent with the Sr-depletion and Y-abundance of many of the Australian Proterozoic granites (Wyborn et al. 1998: op. cit.).

The removal of heat production from the lower crust during granite segregation has important long-term implications for the generation of further granite. The sensitivity of the thermal regime to the depth of burial of anomalous heat production means that segregation of U–Th–K-enriched granites from the lower crust leads to long-term lithospheric cooling. Thus the generation of additional granite is inhibited by two factors: (1) cooler lower-crustal temperatures, and (2) the presence of a moderately anhydrous, refractory lower crust generated during earlier episodes of granite formation. This second point suggests that, unless fertile material can be added to the lower crust, successive generations of granite will require higher temperatures to form. Additionally, a consequence of the long-term cooling associated with the removal of lower-crustal heat production during granite segregation is that any additional melting events will increasingly require the input of external heat.

Wyborn et al. (1998: op. cit.) asserted that the temperatures of formation of Australian Proterozoic I-type granites continent-wide generally increased with time between 1880 and 1500 Ma. For the pre-1700-Ma granites, melting was dominated by minimum melt and biotite breakdown. Most granites formed after 1650 Ma are characterised by amphibole breakdown as the source temperatures reach >1000°C. These higher-temperature granites are represented in the Cu–Au-associated Williams Batholith (Cloncurry area, Qld) and the Hiltaba Suite (Gawler Craton, SA). Further, a plot of Sm–Nd model ages (Fig. 22) shows that granites emplaced between 1500 Ma and 1900 Ma have Model T_{DM} ages >2000 Ma, suggesting that very little material was added to the base of the crust after about 2000 Ma. Therefore, granite production ceased in most of the Palaeoproterozoic provinces by about 1500 Ma, when either fertile source material was completely depleted and/or the higher temperatures required to generate the granites could not be reached.

While the anomalously high-heat-production concentrations are likely to have played a central role in the evolution of the Australian Proterozoic, a fundamental question that is yet to be fully resolved is the reason for the primary enrichment of heat-producing elements to levels up to three times that of normal crust. The Sm–Nd data (Fig. 22), combined with seismic refraction evidence (Goncharov et al. 1997: AGSO Research Newsletter 26, 13–16), suggest that these high values come from mantle-derived material that underplated the lower crust before 2000 Ma. Why this underplate was so enriched at this period of Earth evolution is yet another question awaiting a satisfactory answer.

Acknowledgments

Discussions with Sandra McLaren and Narelle Neumann are greatfully acknowledged as are reviews by Dave Champion and Alan Whitaker. Sue Edgecombe and Shen-Su Sun kindly provided Figure 22. Further information on this, and related topics can be found on the Internet at *http://jaeger.geology.adelaide.edu.au/research.html.*

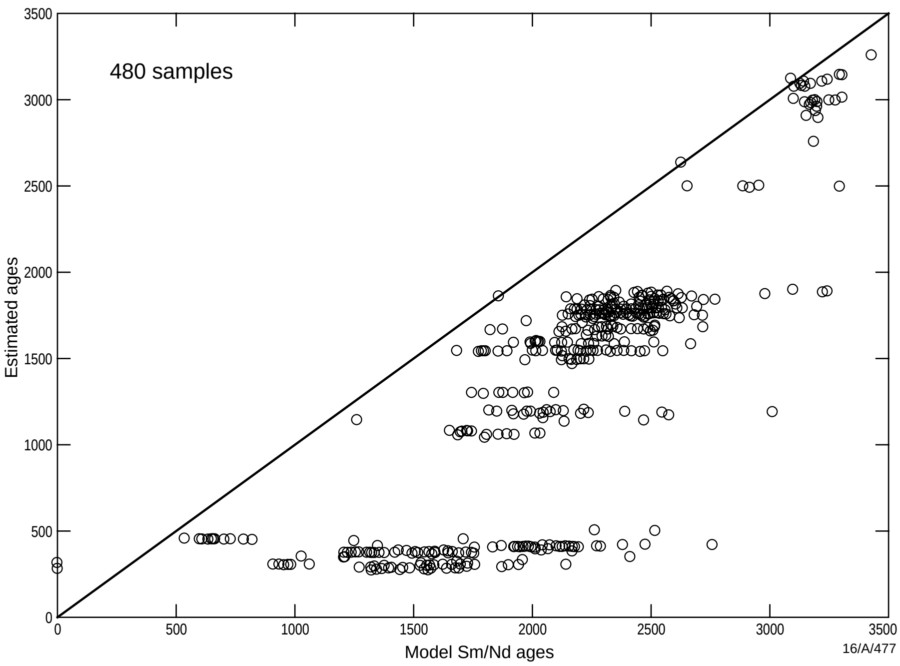

Fig. 22. Model Sm–Nd ages for Australian felsic igneous rocks vs estimated ages (mostly based on zircon ages). Note most samples indicate a pre-existing crustal history and that the bulk of felsic igneous rocks aged between 1900 Ma and 1500 Ma come from source material that is >2000 Ma. All data are from OZCHRON, AGSO's geochronology database.

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