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CHAPTER 12—The hot southern continent: heat flow and heat production in Australian Proterozoic terranes

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Available surface heat-flow measurements from Australian Proterozoic terranes (83 ± 18 mWm–2) are significantly higher than the global Proterozoic average of ~50 mWm–2. Seismic evidence for the presence of relatively cool mantle together with the lack of evidence for neotectonic processes normally associated with thermal transients suggests that anomalous heat flow must reflect crustal radiogenic sources (U, Th and K). This is supported by a compilation of more than 6000 analyses from 455 individual granites, granitic gneisses and felsic volcanics which shows that the present-day average heat production of these rock types is 4.6 μWm–3 when normalised by area of outcrop (over more than 100 000 km2); roughly twice that of 'average' granite. At the time of this felsic magmatism (ca 1850–1500 Ma) heat production rates were some 25–30% greater than the present day such that the total complement of U, Th and K in many parts of the Australian Proterozoic crust may have contributed as much as 60–85 mWm–2 to the surface heat flow, or 2 to 3 times the present-day continental average. This extraordinary enrichment has played a key role in the tectonothermal evolution of the Australian Proterozoic crust, and has important implications for our understanding of the thermal budget of ancient continental crust.

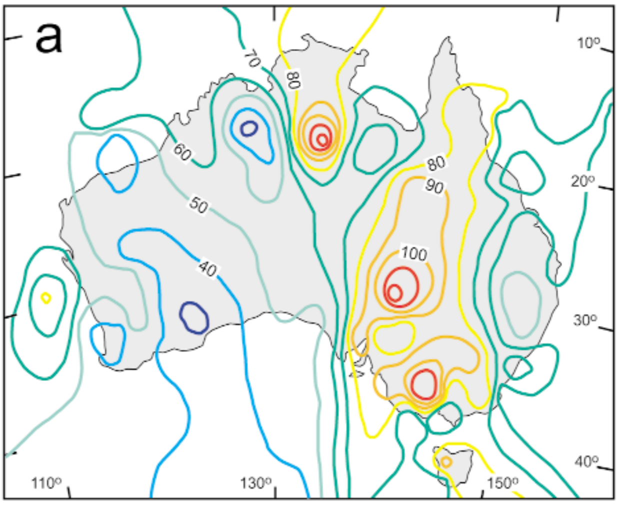
KEY WORDS: continental crust, heat budget, heat flow, Proterozoic, terranes.

INTRODUCTION

In the steady-state, lithospheric thermal regimes are largely controlled by conductive heat loss and reflect both the heat generated internally by the decay of the radioactive isotopes, U, Th and K, and the heat supplied from beneath by the convective mantle (Turcotte & Schubert 1982). Surface heat-flow measurements provide some of the most valuable insights into the nature of lithospheric thermal regimes, as they provide a direct measure of the heat conducted through the outermost part of the lithosphere. Where unaffected by thermal transients associated with climatic, tectonic or groundwater activity, variations in surface heat flow can be attributed to variations in the mantle heat flow, q_m, and/or the abundance of crustal radiogenic sources, q_c.

Detailed surface heat-flow datasets exist for many continental regions, particularly in the United States of America, Western Europe and the former USSR (Pollack *et al.* 1993), whereas the heat-flow field from Antarctica, South America, Australia, and most parts of Africa, is much less well constrained. The available global data imply that surface heat flow increases from the Archaean (41–46 mWm^{-2}) into the Proterozoic (49–54 mWm^{-2}) and again into the Phanerozoic (50–70 mWm^{-2}) (Chapman & Furlong 1977; Morgan 1984; Nyblade & Pollack 1993). The global mean value for the continental crust is 65 ± 1.6 mWm^{-2} (Pollack *et al.* 1993) of which around 30 mWm^{-2} is attributed to radiogenic heat production within the crust (i.e. q_c) with the remainder due to heat supplied to the lithosphere by convective processes in the deeper mantle (McLennan & Taylor 1996).

As a result of the geographic bias in the global heat-flow dataset, the natural range in surface heat flow and the relative contributions of crust and mantle sources are, potentially, only poorly understood (see also Jaupart & Mareschal 1999). For example, Neumann *et al.* (2000) recently showed that anomalous heat flow (~90 mWm^{-2}) from a Proterozoic terrane in South Australia correlates with extreme surface heat-production rates relative to the Proterozoic global average. In this paper we extend this analysis of surface heat-flow data across all mainland Australian Proterozoic terranes and show that almost all are characterised by anomalous concentrations of the heat-producing elements. We begin by outlining the evidence for anomalous surface heat flow and present the first detailed analysis of surface heat production at the scale of the continent, as well as other data to constrain the relative contributions to the observed heat flow in these regions. This analysis shows that in these terranes the average surface heat flow of ~80 mWm^{-2} reflects a crustal contribution of at least 50–65 mWm^{-2}, roughly twice that expected on the basis of the 'global-average' continental crust (McLennan & Taylor 1996). The anomalous enrichment of the heat-producing elements has significant implications for the tectonothermal evolution of Proterozoic terranes, and for our understanding of the range, and sources of variability, of heat flow at global and continental scales.



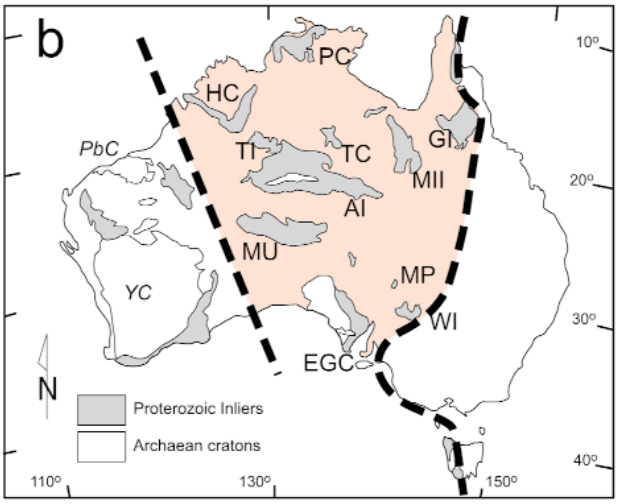


Figure 1 (a) Major features of the Australian heat-flow field (image from Cull 1982 with contours from a 1° grid of values). Contour interval 10 mWm^{-2}. (b) Location of Proterozoic metamorphic belts and Archaean cratons. The Central Australian Heat-Flow Province is shown in red and the thick dashed lines delineate the Western and Eastern Provinces. HC, Halls Creek Inlier; MII, Mt Isa Inlier; TC, Tennant Creek Inlier; MP, Mt Painter Inlier; AI, Arunta Inlier; TI, Tanami Inlier; WI, Willyama Inliers; MU, Musgrave Block; EGC, Eastern Gawler Craton and Stuart Shelf; PC, Pine Creek Inlier; GI, Georgetown Inlier; YC, Yilgarn Craton; PbC, Pilbara Craton.

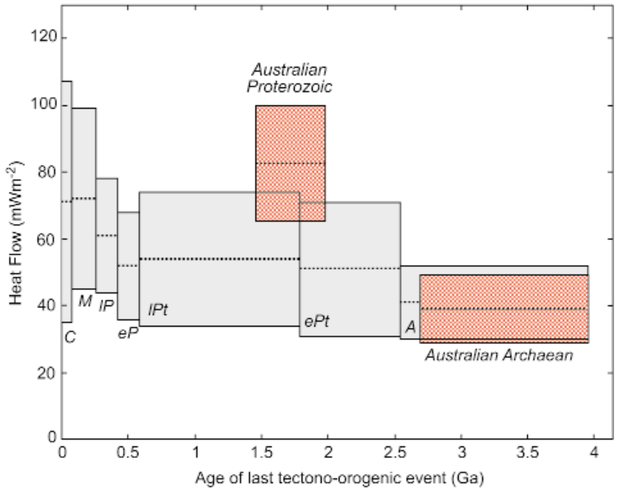


Figure 2 Histogram of global continental modern surface heat-flow data from Morgan (1984). Heat-flow measurements are grouped with age based on the timing of the last major tectonothermal event in the region of the measurement. A, Archaean; ePt, Early Proterozoic; lPt, Late Proterozoic; eP, Early Palaeozoic; lP, Late Palaeozoic; M, Mesozoic; C, Cenozoic. For each grouping, average heat flow is denoted by the dashed line, boxes show regions of 1s in the heat flow and the range of ages (Morgan 1984). The red boxes are the age range and the average (± 1s) of modern surface heat-flow data from Australian Proterozoic (using only 'good' quality determinations) and Australian Archaean terranes.

AUSTRALIAN HEAT-FLOW FIELD

In comparison with many continental settings, the Australian heat-flow field is poorly constrained with only ~120 data points (Cull 1982). Sass and Lachenbruch (1979) undertook the first detailed synthesis at the continental scale dividing the heat-flow field into the Eastern, Central and Western Provinces (Figure 1) based on the regression of surface heat-flow and heat-production data (Lachenbruch 1968, 1970). This tripartite division is closely allied to tectonic age. The dominantly Archaean Western Province has an average heat flow of 39 ± 8 mWm^{-2}, consistent with accepted global averages for the Archaean ((Chapman & Furlong 1977; Morgan 1984). In the Eastern Province, where the major period of crustal growth occurred in the Palaeozoic and where widespread Cenozoic magmatism is concentrated, heat-flow averages 72 ± 27 mWm^{-2}, somewhat higher than, but within error of, accepted global averages for Phanerozoic terranes (Morgan 1984). In contrast, in the Central Province, here termed the Central Australian Heat-Flow Province, surface heat-flow averages 82 ± 25 mWm^{-2} (using all measurements from 48 distinct locations). The Central Australian Heat-Flow Province comprises the region of the Australian continent formed mostly during the Proterozoic (Figure 1) and its high surface heat flow is well in excess of the 49–54 mWm^{-2} expected on the basis of the global average of equivalently aged terranes (an average which includes the Australian data: (Chapman & Furlong 1977; Morgan 1984). The unusually high heat-flow measurements from the Australian Proterozoic must arise as a consequence of either: (i) systematic error or bias in the heat-flow determinations; (ii) anomalous mantle heat flow, q_m; (iii) recent tectonic, magmatic or hydrologic activity; or (iv) an anomalous contribution from crustal heat sources, q_c. Each of these possibilities is discussed in the following section.

ORIGINS OF ANOMALOUS HEAT FLOW IN THE AUSTRALIAN PROTEROZOIC

Potential errors associated with the collection of both thermal gradient and thermal conductivity data may contribute to errors in the calculated surface heat flow. Moreover, in each case the condition of the borehole and its physical environment will also impact on the quality of the heat-flow

Table 1 Surface heat flow and heat production within Proterozoic metamorphic belts of the Central Australian Heat Flow Province (CAHFP).

Metamorphic terrane	qs (mWm^{-2}) measurements	qs (mWm^{-2}) average	Q (μWm^{-3})	Area (km^2)[a]	Metamorphic pressure (MPa)	Source
Willyama Inliers	80, 68, 64, 75	72	2.9	1920	400–600	Wilson & Powell 2001
Mt Painter Inlier	**		16.1	555	300–400	Mildren & Sandiford 1995
Eastern Gawler Craton & Stuart Shelf	91, 91, 73, 120	94	4.8	20888	500–700	Drexel *et al.* 1993
Mt Isa Inlier	82, 78, 72, 98	83	4.8	10935	400	Rubenach 1992
Georgetown Inlier	77, 100	89	5.1	6411	300–500	Withnall 1996
Tennant Creek	89, 100, 100	96	3.9	4131	300–400	Donnellan *et al.* 1995
Pine Creek	86, 84, 80	83	4.7	8626	300–500	Ahmad 1998
Arunta Inlier	62, 56	59	5.2	27233	600–900 (Central) 400–500 (South/North)	Arnold *et al.* 1995 Hand *et al.* 1992
Tanami Inlier	**		5.8	790	350	Scrimgeour & Sandiford 1993
Halls Creek	65, 67	66	3.2	12073	350–500	Bodorkos *et al.* 1999
Musgrave Inlier	–		2.7	5499	1200–1300 (South) to 600–700 (North)	Scrimgeour & Close 1999
CAHFP AVERAGE		82.6 ± 17.7	4.6	100477		

Only 'good' quality heat flow determinations from Cull (1982) are listed. Lesser quality data are available for terranes indicated (**). Terranes shown in Figure 1. CAHFP averages include all 'good' quality heat-flow determinations and all surface heat-production data, including some regions not listed here.

Q = present day granite heat production, averaged by proportional outcrop area and calculated from present concentrations of U, Th, and K (raw data from Wyborn *et al.* 1998; Mt Painter data from Neumann *et al.* 2000).

[a] Total area is that area of outcrop of felsic igneous rocks for which heat-production data are available. Total area listed is used in the calculation of area normalised heat-production averages.

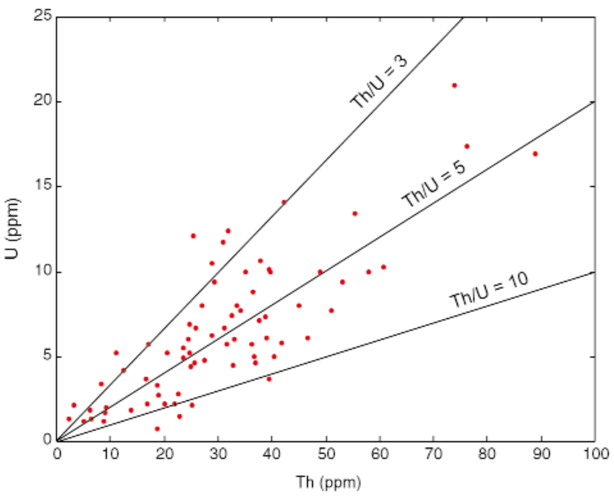


Figure 3 Average U and Th data for all 76 supersuites (Wyborn *et al.* 1998). Also shown are regression lines for Th/U = 3, 5 and 10. The average Th/U ratio for all Australian Proterozoic felsic igneous rocks when normalised by area of outcrop is 4.7.

measurement. Cull (1982) evaluated sources of potential errors and concluded that 75% of the Australian heat-flow data were of 'good' quality or better (that is ±15%) , including more than 60% of the data from the Central Australian Heat-Flow Province. The question of a systematic bias can be assessed by comparison of analyses from Archaean and Proterozoic terranes. There is no obvious reason why systematic polarity or bias in measurements resulting from the technique should be sensitive to geological attributes of a terrane, such as age. Consequently, the absence of any systematic bias in the heat-flow determinations from Australian Archaean terranes when compared with the global dataset (Figure 2) argues against the Proterozoic measurements being systematically biased.

Transient thermal pulses giving rise to elevated heat-flow measurements can be associated with recent tectonic or magmatic activity, climate change or to sustained, rapid denudation. Unlike well-known terranes like the Basin and Range Province in southwestern USA (Sass *et al.* 1994), there is little evidence for recent tectonic or magmatic activity in the Central Australian Heat-Flow Province (aside from a small region in South Australia which suffered mild neotectonic reactivation associated with the formation of the Flinders Ranges: Sandiford 2002). Indeed the vast majority of crust in the Central Australian Heat-Flow Province has remained relatively tectonically inactive for the last few hundreds of millions of years. This tectonic quiescence is reflected by exceptionally low denudation rates (cf. Bierman 1994) of <1–1.5 m/10^6 y, determined by cosmogenic nuclide dating (Bierman & Turner 1995). Such denudation rates, which represent the time integrated rate over at least the last 0.5 million years, are far too slow to produce any apparent steepening of the geotherm and thus can be excluded as a possible cause for the regionally elevated heat-flow determinations. Climatic effects (Bowler *et al.* 1976), which could introduce systematic errors at the continental scale, would not be expected to bias the measurements in Proterozoic terranes independently of Archaean terranes and thus are discounted as a source of systematic bias.

A compilation of both refraction and reflection seismic data suggests that Proterozoic terranes throughout central Australia (comprising a large proportion of the Central Australian Heat-Flow Province) contain the thickest crust within the Australian continent, with the Moho discontinuity typically imaged at around 45 km (Drummond 1988; Collins 1991). Deep seismic imaging suggests that this thick crust is coupled with relatively cool, thick lithosphere; with the transition to slow seismic velocities associated with sub-lithospheric mantle imaged at around 250 km (Kennett & van der Hilst 1996). Shear-wave velocities in the Proterozoic upper lithospheric mantle at 80 km depth beneath the Central Australian Heat-Flow Province are about 6% faster than velocities beneath Eastern Australia (Zielhaus & van der Hilst 1996), where marginally elevated surface heat flow is attributed to anomalous mantle heat flow (Sass & Lachenbruch 1979). If the variations in shear-wave velocity are essentially thermal in origin the temperature difference between the regions is estimated to be around 200°C (Zielhaus & van der Hilst 1996; Goes *et al.* 2000). Consequently, the existence of thick, cold mantle lithosphere beneath much of the Central Australian Heat-Flow Province points to low mantle heat flow throughout this region. Using Fourier's Law, for thermal conductivities of 3.0 ± 0.5 $Wm^{-1}K^{-1}$ appropriate to mantle peridotite at elevated temperatures (Haenel *et al.* 1988) and Moho temperatures of 400–500°C at 40 km depth, a lithospheric thickness of 250 km implies present-day mantle heat flows of ~10–15 mWm^{-2}.

In order to explain the anomalous surface heat flow in the Central Australian Heat-Flow Province by crustal heat production, radiogenic heat sources must contribute up to ~70 mWm^{-2}. This can be compared with estimates of typical crustal contributions from McLennan and Taylor (1996 p. 369) who argued that the 'radiogenic component of (average) continental heat flow must lie within the range of 18–48 mWm^{-2}, and almost certainly lies within the range of 21–34 mWm^{-2}' A total complement of heat-producing elements of ~70 mWm^{-2} in the Australian Proterozoic terranes implies an average crustal heat production of around 1.6 μWm^{-3}, about 50% greater than estimates of crustal average heat production of around 0.6–1.2 μWm^{-3} (Rudnick & Fountain 1995; McLennan & Taylor 1996; Rudnick *et al.* 1998). Since lower crustal rock types are typically depleted in heat-producing elements relative to middle and upper crustal rocks, upper crustal heat-production rates must be significantly higher than the crustal average.

Regional-scale, bulk-crustal enrichments of the heat-producing elements should be expected to be reflected in the surface heat-production rates of characteristic upper

Table 2 Heat production of major granite suites in the Central Australian Heat Flow Province

Terrane	Granite	Age range (Ma)	Outcrop area (km^2)	U (ppm)	Th (ppm)	K (wt%)	Q (μWm^{-3})
EGC	Minbrie Gneiss	ca 1800	899	4.6	36.9	5.27	4.5
	Hiltaba Supersuite	ca 1580	19419	7.4	32.6	4.98	4.8
MII	Kalkadoon	1850–1800	4686	5.3	25.6	4.71	3.7
	Rift-related	1750–1650	4323	6.6	33.5	5.60	4.7
	Williams & Naraku	ca 1500	1883	13.5	55.5	3.90	7.9
GI	Esmeralda	1550	4664	10.5	28.8	5.08	5.3
	Forsayth	1550	1681	6.7	31.1	4.59	4.5
TC	Tennant Creek	1850	2195	5.5	23.4	4.60	3.6
	Treasure Suite	1820	1493	6.0	24.5	5.08	3.8
	Devils Suite	1710	443	8.7	36.4	5.23	5.5
PC	Cullen	1890–1825	8325	7.3	31.9	4.53	4.7
	Burnside	1800–1760	300	11.1	38.1	4.85	6.2
AI	Napperby	ca 1780	6041	10.3	60.7	5.30	7.6
	Madderns Yard	1680–1650	4001	2.2	20.2	3.03	2.3
	Southwark	1680–1570	1996	7.7	51.1	5.00	6.2
	Mt Webb	1480	5623	10.0	39.7	4.46	6.0
TI	The Granites	1820	784	11.7	31.0	5.20	5.8
HC	Paperbark Suite	1860–1850	9415	5.2	20.6	4.48	3.3
	Sally Downs	1820	2592	3.6	19.0	3.46	2.7
MU	Kulgera Suite	1200–1150	3639	1.5	22.8	4.26	2.5
	Winburn Suite	1200	1783	5.8	41.8	4.66	5.0
TOTAL[a]			100477	6.8	32.1	4.62	4.6
		1650–1480 Ma (79)	37328	8.6	35.6	4.83	5.3
		1800–1650 Ma (117)	23565	6.7	38.4	4.58	5.0
		1850–1800 Ma (94)	13788	7.0	28.8	4.68	4.4
		Pre 1850 Ma (70)	19612	4.8	22.0	4.31	3.3

Heat production is that of the present day, based on present abundances of the heat-producing elements, as shown. Average U, Th and K data summarised from Wyborn *et al.* (1998). Terrane abbreviations given in Figure 1.

[a] TOTAL values are determined from an average of all analyses (including granites not listed above). Binned age averages include all granites for which age and heat production data are available. The number shown in parentheses is the number of map-scale units used in each average.

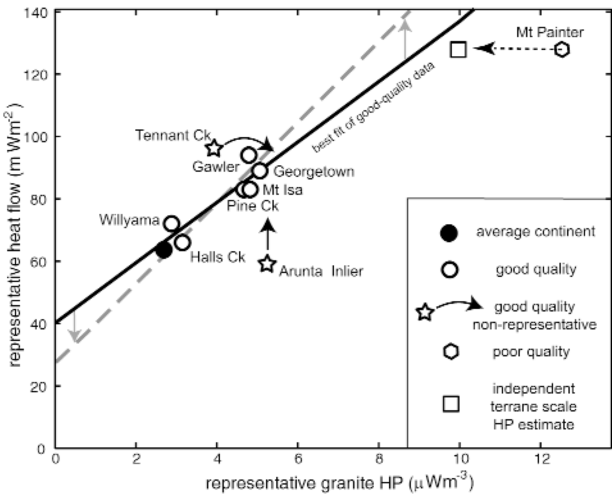


Figure 4 Average heat-flow and granite heat-production data for Proterozoic terranes for which 'good' quality heat flow determinations are available (Cull 1982). The solid line is the best-fit regression for the data (excluding the Arunta, Tennant Creek and Mt Painter values). The dashed line is the heat flow – heat production relationship for our best estimate of the true reduced heat flow, and corresponds to what would be expected for a distribution which varied on very large horizontal length scales (>500 km). Note that the Mt Painter data are consistent if an independent terrane-scale estimate of average heat production within all Mt Painter rocks (including metasediments: Sandiford *et al.* 1998) is used.

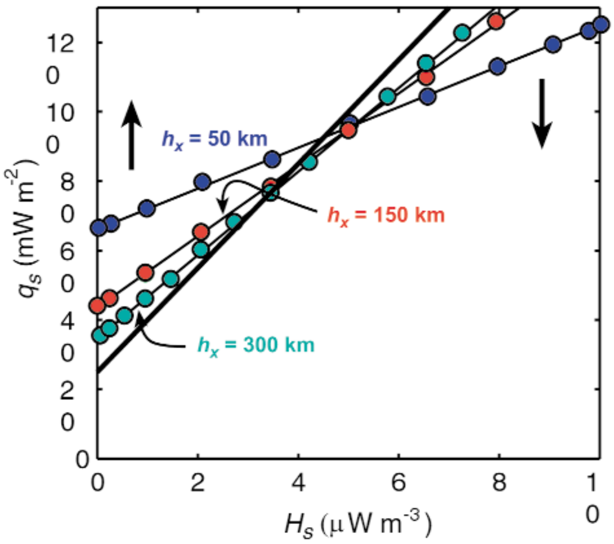
crustal lithologies such as granites. Granites (and granite gneisses and felsic volcanics) provide a useful lithology on which to base such a comparison, because: (i) they represent one of the main lithologies in the mid-upper crust; (ii) they host a major proportion of the crustal complement of heat-producing elements; and (iii) the compositional spectrum of granites is now well understood, providing an exceptional framework against which to measure regional variations. Here we use an extensive geochemical database of Australian Proterozoic felsic igneous rocks compiled by Wyborn *et al.* (1998). Granites and granite gneisses constitute a significant proportion of Australian Proterozoic terranes, both in outcrop and in the subsurface, as revealed by seismic profiling (Drummond *et al.* 1998). The U, Th and K whole-rock geochemical data in the Wyborn *et al.* (1998) dataset are compiled from 6410 analyses representing 455 different map-scale units and 76 distinct supersuites from all mainland Australian Proterozoic terranes (see Appendix 1 for notes on the geochemical data). Present-day heat-production values were calculated from these data using known decay parameters (Turcotte & Schubert 1982), and normalised by proportional outcrop area to eliminate possible bias arising from highly radiogenic but small volume lithologies. In evaluating the available data we also consider calculated Th/U ratios (Figure 3). All of the supersuites have relatively low Th/U ratios with only four supersuites averaging more than 10. Although Th/U ratios in the range of 3–5 are commonly interpreted to represent unaltered primary igneous enrichment, igneous Th/U ratios are known to be much more variable (Adams *et al.* 1959) such that higher or lower values do not necessarily reflect secondary enrichment (cf. Durrance 1986). Indeed Adams *et al.* (1959) showed that many important Th- and U- bearing phases (including zircon, monazite, thorite and xenotime) have a wide range of Th/U. Consequently the two elements do not necessarily show parallel variation. This is probably the case for the Australian Proterozoic granites where the majority of the Th and U is contained within primary accessory phases which appear to have crystallised prior to, or together with, the main rock-forming minerals.

In terms of the regional dataset, heat production of felsic granites and volcanics in all Proterozoic terranes within the Central Australian Heat-Flow Province averages 4.6 μWm^{-3} when normalised by area of outcrop (Table 2), some 1.8 times that of the average granite (2.5 μWm^{-3}: Haenel *et al.* 1988). This value is even more extraordinary given that the total area of outcropping granite on which it is based (in excess of 100 000 km^2) often represents more than 20% of the outcrop at the terrane scale (Wyborn *et al.* 1992; McLaren & Sandiford 2001).

In all terranes heat-production rates also show significant trends with intrusive age (Table 2). The oldest Palaeoproterozoic Barramundi Suite granites are the lowest heat producing (in the range 1.5–3.6 μWm^{-3}) while the Early to Middle Mesoproterozoic granites are generally the highest heat producers. Examples of the latter include the 1545–1490 Ma Williams and Naraku Batholiths in the Mt Isa Inlier (7.9 μWm^{-3}), 1570–1555 Ma granites in the Mt Painter Inlier (16.1 μWm^{-3}) and the 1570 Ma Southwark granite suite in the Arunta Inlier (6.2 μWm^{-3}) (Table 2). Regardless of age, however, almost all of the Australian Proterozoic granites are I-type and characteristically depleted in strontium, but not depleted in yttrium, reflecting derivation from moderately shallow sources in which plagioclase, but not garnet, was stable (Wyborn *et al.* 1992). These data suggest that many of these Proterozoic granites have experienced a significant crustal prehistory, and mostly reflect crustal recycling rather than new additions from the mantle. This assertion is also supported by isotopic data which shows that the majority of the granites have negative e_{Nd} values (McCulloch 1987; Wyborn *et al.* 1992) which are generally similar to the Nd isotopic signature of the associated Proterozoic basement rocks.

HEAT FLOW–HEAT PRODUCTION RELATIONS

Although average heat flow and heat production in the Central Australian Heat-Flow Province are high, in detail there is considerable variation in the heat flow – heat production relations at the continental scale (Figure 4). Figure 4 shows the granite heat-production data plotted as function of heat flow for each of the terranes for which heat-flow data of 'good' quality are available (Cull 1982). Also included is the Mt Painter province where a single heat-flow measurement (126 mWm^{-2}) was rated by Cull (1982) to be of poorer quality on the basis of its proximity to the rejuvenated Mt Painter escarpment. The eight 'good' quality data points shown in Figure 4 define a considerable spread, which on initial inspection, suggests that our assumption that exposed granites provide a representative view of bulk crustal heat-production rates may be invalid.



h_x	h_r (km)	q_r (mWm^{-2})
50	5.9	65.4
100	8.8	51.0
150	**10.3**	**43.6**
200	11.2	39.3
300	12.0	34.3
500	12.9	29.9
OBSERVED	**10**	**40**

Figure 5 Effect of lateral conduction on the linear heat flow – heat production relationship (Jaupart 1983). The solid line shows the heat flow – heat production relationship for our best estimate of the actual Central Australian Heat-Flow Province values: h_r = 13 km and q_r = 25 mWm^{-2}. The horizontal length scale, h_x, of a simple homogeneous heat source distribution with the same parameters was then varied to investigate the effect of lateral conduction. Arrows show the rotation effect as the horizontal length-scale decreases. The apparent h_r and q_r values for different h_x are shown in the table and the best fit to the observed 'good' quality data implies a horizontal length-scale of around 150 km. For very large horizontal length-scales (h_x >500 km) the modelled heat flow – heat production relation closely matches our best estimate of the actual values.

In particular the Tennant Creek and Arunta Inlier data seem anomalous. However, the Arunta Inlier is unusual amongst the Australian Proterozoic terranes, as it has suffered extensive Palaeozoic tectonism (Collins & Teyssier 1989; Shaw *et al.* 1992) resulting in locally deep levels of denudation with the consequent exposure of largely depleted, mafic deep crustal rocks. The heat-flow field of the Arunta Inlier is therefore likely to reflect this Palaeozoic denudation, with erosion of the high heat-producing upper crust biasing heat-flow measurements to lower values. Moreover, the Alice Springs heat-flow measurement (62 mWm^{-2}) is located near one of the lowest heat-producing felsic suites in the region (the Atnarpa Igneous Complex with an area-normalised heat-production rate of just 0.3 μWm^{-3}). This further supports the notion that the available heat-flow data may be biased to lower than characteristic values.

The relatively low average heat production in the Tennant Creek Inlier (when compared to its high surface heat flow) is more problematic. In this terrane, there is a relatively small number of analyses and a comparatively small area of exposure of granitic lithologies. Of the two main granite suites (Table 2) surface exposures are dominated by the lower heat-producing mid-Palaeoproterozoic Tennant Creek and Treasure suite granites. In contrast, the high heat-producing Devils Suite outcrops only to a limited extent, but is interpreted to be more extensive in the subsurface in the area of the heat-flow measurements suggesting that the proportion of granite types in the surface exposures is not representative of the crust as a whole. In this case, the representative granite heat production derived from surface exposures is likely to be an underestimate, while the heat-flow measurement may be biased to somewhat higher than average values.

In the remaining six terranes for which there are 'good' quality heat-flow data there is a clear correlation between the measured heat flow and the representative granite heat production, supporting the notion that anomalous crustal heat production contributes to the heat-flow anomaly. The two lowest heat-flow terranes (Willyama and Halls Creek) are characterised by granite heat-production rates only slightly greater than the global 'average' granite, with heat flow values similar to the global continental average. In contrast heat-production rates in granites from the Mt Isa, Georgetown and Pine Creek Inliers and the eastern Gawler Craton are about twice the 'average' granite, and heat flow is significantly higher than typical Proterozoic values.

Figure 4 also shows the line of best-fit to the heat flow – heat production data; a relationship which is often used to make inference on the heat-production distribution in the region of the heat-flow measurements. Following Lachenbruch (1968) and Birch *et al.* (1968), the y-intercept is interpreted as the reduced heat flow (q_r) and the slope is the characteristic length scale (h_r). The reduced heat flow provides a measure of the deep crustal and mantle contributions to the surface heat flow, while h_r is a measure of the thickness of the enriched upper crustal layer that accounts for the observed spatial variations in the surface heat flow. For the Central Australian Heat-Flow Province data shown in Figure 4, h_r is 10 km and q_r is 40 mWm^{-2}.

However, as noted by England *et al.* (1980) and Jaupart (1983), lateral heat transfer associated with lateral variations in heat production necessarily results in a horizontal 'averaging' over the region where the heat flow is measured. Consequently, measured heat flow – heat production relations overestimate q_r and underestimate h_r. Such lateral heat transfer produces a clockwise rotation of the best-fit lines on diagrams such as Figure 4, with the amount of rotation dependent on the characteristic horizontal length-scale of the heat-production variation (Jaupart 1983). There are few data concerning the characteristic horizontal length scales for heat production, and thus the degree of rotation implicit in observed heat flow heat – production relations is not well understood. Nevertheless, a rough estimate of the characteristic length scale can be obtained by constraining the correct reduced heat flow, and investigating the way in which the linear relationship changes as the horizontal heat-production length-scale, h_x, is varied.

Table 3 Surface heat flow, heat production and metamorphic pressure for major Laurentian and South African Proterozoic terranes.

Terrane	q_s (mWm^{-2}) average	Hp* (μWm^{-3})	Source	Metamorphic pressure (MPa)	Source
Grenville	41 ± 11	0.8	Guillou *et al.* 1995	~1100	Ketchum *et al.* 1994; Indares 1995
Trans-Hudson	42 ± 11	0.6 ± 4	Mareschal *et al.* 1999	600-1100	Mengel & Rivers 1997; St-Onge *et al.* 2000
Svecofennian	35-55	1.5-3.5	Kukkonen & Joeleht 1996 Balling 1995	600-900	Knudsen 1996
Namaqua	61 ± 11	2.3	Jones 1987	500-700	Clifford *et al.* 1981; Raith 1995

Grenville, Trans-Hudson and Namaqua heat-flow and heat-production data from the compilation of Jaupart & Mareschal (1999).

As noted above, the mantle heat flow for Australian Proterozoic terranes is estimated at no more than ~15 mWm^{-2}, providing a minimum bound on the reduced heat flow. Additional heat production in the lower crust also contributes to the reduced flow field, with estimates of the ratio of average upper crustal to lower crustal heat production of ~5 implied by analyses of the vertical distribution of heat production in continental crust (Lachenbruch 1970). For the Australian Proterozoic this implies a lower crustal contribution of ~10 mWm^{-2} giving a corrected reduced heat flow of ~25 mWm^{-2}. We use this to define our best estimate of the 'actual' parameters of the heat-production distribution in the Central Australian Heat-Flow Province crust (Figure 5). We then investigated the way in which this heat flow – heat production relationship changes using a simple homogeneous distribution with the same parameters, but which varies on different horizontal length scales (Figure 5). Comparison of these different models with the heat flow – heat production relationship that is observed (i.e. h_r ~10 km, q_r ~40 mWm^{-2}) gives some estimate of the horizontal length scale of the heat production variation. For the Central Australian Heat-Flow Province the observed best fit implies a horizontal length scale of ~150 km.

DISTRIBUTION OF HEAT SOURCES

The heat flow–heat production relations described here suggest that heat sources within the Central Australian Heat-Flow Province are distributed over finite vertical and horizontal length scales.

In terms of the vertical distribution, our best estimate of the actual reduced heat flow gives a slope of 13–15 km (Figure 4). This provides a measure of the typical thickness of the enriched upper crust (which is independent of the specific analytical form of the distribution). This conclusion is supported by the variations in heat production observed across obliquely exposed crustal sections in both the Arunta and Musgrave Inliers (Figure 6). In the southern Arunta Inlier, felsic and mafic granulites are thrust over Palaeoproterozoic to Mesoproterozoic metasediments and granitic rocks, providing an oblique crustal section through the mid-lower crust, and the mid-upper crust (Figure 6a) (Sandiford *et al.* 2001). Comparison of average heat production and estimates of metamorphic pressure suggest that below around 10 km heat productivity declines significantly with depth (Figure 6b). This is also the case in the deeply denuded parts of the Musgrave Province, where the exposure of different crustal levels in the Mann Ranges allows a synthetic heat production vs depth profile to be constructed (Figure 6c). Here, rocks that were at depths greater than around 25 km (~700 MPa) are characterised by relatively constant heat-production values in the range 1.3–2.3 μWm^{-3}. In contrast, a discrete zone between around 17–25 km is characterised by much higher average heat production in the range 4.6–6.0 μWm^{-3}. Both of these examples provide evidence for asymmetry in the vertical heat-production distribution.

In terms of the lateral distribution, the rotation of the linear heat flow–heat production relationship suggests upper crustal heat production varies on a horizontal length scale of around 150 km. Although this is clearly a rough estimate, it provides the first measure of the scale of lateral variation in heat production in the Australian continental crust. Lateral variations in basement heat production of this scale are supported by the presence of several lower heat-flow measurements between the high heat-flow zones (for example between the Mt Isa and Tennant Creek regions: Figure 1).

DISCUSSION

Given that internal heat sources contribute to the lithospheric thermal budget (Turcotte & Schubert 1982), the anomalous concentrations of heat sources in Australian Proterozoic crust are likely to have impacted significantly on the thermal history of these terranes. Quantifying these effects requires consideration of both the absolute abundance of crustal heat sources in the past, and also their distribution prior to and during metamorphism, magmatism and crustal differentiation. We have shown that for the present-day surface heat flow of around 80–85 mWm^{-2} the crustal contribution is on average 50–70 mWm^{-2}. During the Proterozoic this crustal contribution is likely to have been greater because: (i) barometric estimates suggest that around 10–15 km of the upper crust has been removed from many Australian Proterozoic terranes by post-metamorphic exhumation (Table 1); and (ii) the decay of the main heat-producing elements results in a significant decrease (around 20–25% for typical granitic compositions) in heat production over the appropriate time intervals (1800–1500 Ma). Each of these factors would contribute a further 15–20 mWm^{-2} to the total crustal contribution in the past. On the other hand, significant crustal shortening

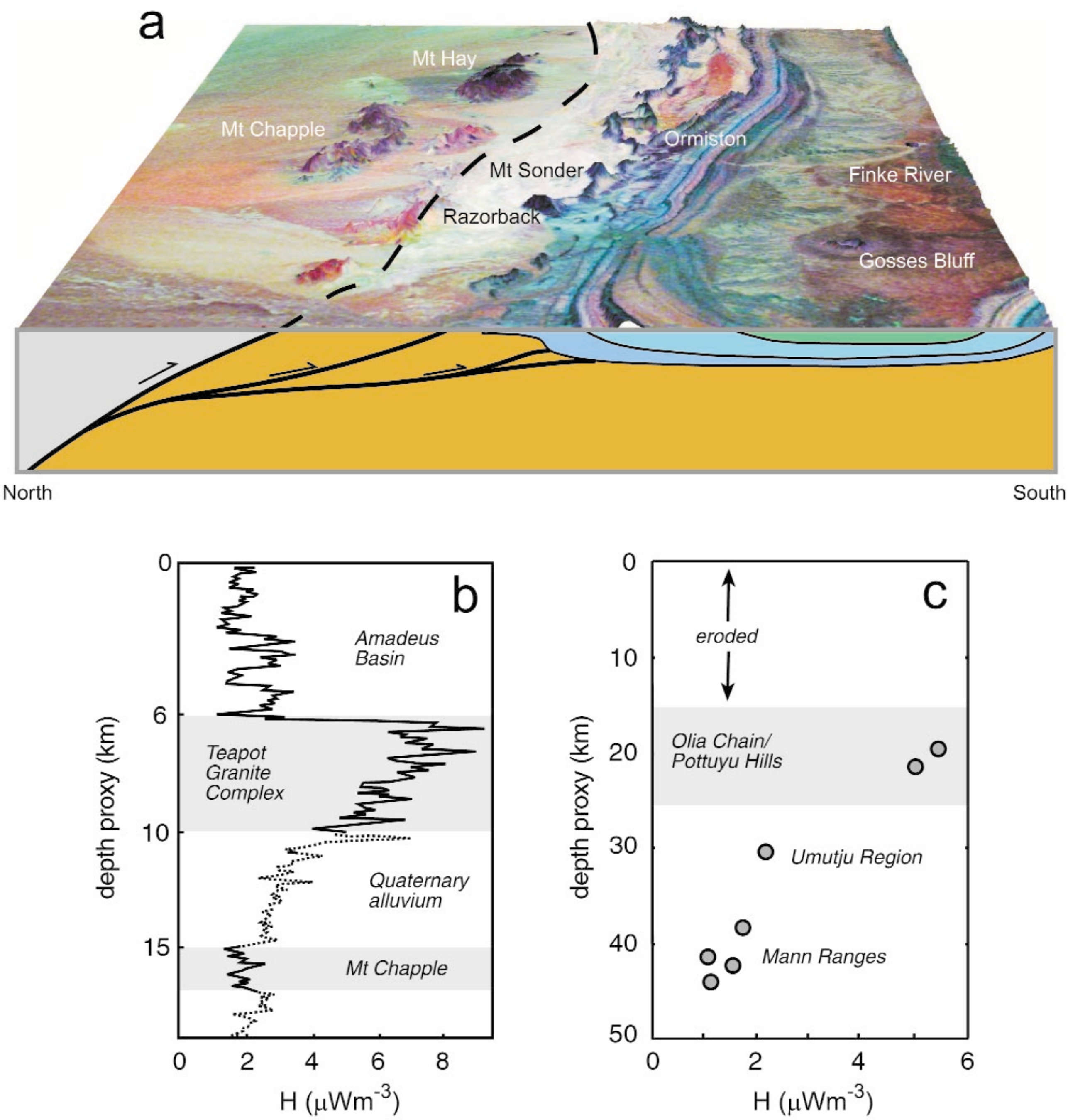


Figure 6 (a) Oblique heat-production image of a portion of the western Arunta Inlier, Northern Territory (Figure 1) derived from Northern Territory Geological Survey airborne radiometric data. (b) Heat production vs depth profile constructed for the crustal section exposed in this region. (c) Heat production vs depth profile for a section of the Musgrave Ranges, based on average geochemistry and heat-production values from Scrimgeour & Close (1999). The Musgrave section shows the pre-deformational heat-source distribution applicable at the time of peak metamorphism (ca 560–520 Ma). The Arunta section shows the inferred distribution prior to denudation during the Alice Springs Orogeny (ca 350 Ma). Note different depth scales.

recorded in many terranes prior to effective cratonisation is likely to have increased the thickness of the heat-producing units and this repetition is likely to cancel the second point above, at least at the first order. Notwithstanding these considerations, constraints outlined here suggest that the thermal and tectonic evolution of Proterozoic terranes in Australia should be viewed in the context of a total crustal contribution almost two times the value expected from global heat-flow averages.

The fundamental questions raised by the Australian Proterozoic observations relate to the origin of the extraordinary enrichment in heat-producing elements, and to their preservation. Although the Australian Proterozoic case is clearly unusual in terms of accepted global means, it is not necessarily clear whether it represents a unique geochemical anomaly, or is more a consequence of preservation. As noted above, most Australian Proterozoic terranes have experienced very low average levels of denudation (~10–15 km). Consequently, most of the enriched granitic mid-upper crust is preserved. In contrast, many Proterozoic terranes from other parts of the world, including the Grenville Province (Table 3), are characterised by significantly deeper levels of denudation with the preserved crust on the whole more refractory. The lower heat flow of other Proterozoic terranes is therefore at least in part due to deeper levels of denudation. Indeed, it is striking that the most deeply denuded portions of the Australian Proterozoic, in both the Musgrave and Arunta Inliers, are characterised by relatively low heat-production values (Figure 6). Whether or not this assertion is strictly correct, recognising that the modern crust generally does not preserve complete sections of the ancient crust has important implications for our understanding of crustal thermal budgets. Generally, inferences on the crustal contribution to lithospheric thermal regimes are made using modern heat-flow relations (Taylor & McLennan 1985). While this methodology is appropriate for understanding modern thermal regimes, the conclusions which are drawn from these studies (McLennan & Taylor 1996) are often applied to ancient crustal systems without consideration of the configuration of that crust, and particularly the nature of the upper crustal material that has since been removed by erosion. The Australian Proterozoic data discussed here show that the variability in heat-production parameters for continental crust can be extreme, and provide new insights into the nature of crustal thermal regimes during the evolution of the early Earth.

The high crustal contributions to surface heat flow described here have important implications for temperature-dependent crustal processes, including metamorphism, magmatism and deformation. Although the impact of the presence of heat-producing elements within the crust has begun to be evaluated in regions of already thickened crust (Huerta *et al.* 1998, 1999; Bea *et al.* 1999; Gerdes *et al.* 2000; Attoh 2000) the Australian Proterozoic case highlights the need to carefully consider the contribution of radiogenic heat sources to the long-term thermal evolution of the lithosphere. This approach may provide insights into the evolution of ancient terranes in which the controls on thermal processes have remained enigmatic.

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APPENDIX: 1 X-RAY FLUORESCENCE SPECTROMETRY

U, Th and K analyses in the Wyborn *et al.* (1998) dataset were obtained using X-Ray fluorescence spectrometry on whole-rock powders. Although many of these data came from a wide variety of government and university research programs, detection limits for U and Th using this technique are ~ 1.5 ppm, with accuracy estimated at ± 5% at 100x detection limit. For potassium analyses accuracy is estimated at ± 0.02%. These detection limits are only important for samples containing low concentrations of these elements (i.e., for a sample of heat production = 3 μWm^{-3} the error is ± 17% whereas for a sample of heat production = 6 μWm^{-3} the calculated error is only ± 8%).