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# Magmatism, orogeny and the origin of high-heat-producing granites in Australian Proterozoic terranes

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## ABSTRACT

**Temperature-dependent processes like magmatism and orogeny provide key insights into the Earth's thermal state. We propose an integrated model for the origin of voluminous Proterozoic-aged granitic rocks in northern Australia, suggesting that the observed large range of concentrations of incompatible elements (particularly U, Th and K) was established progressively as a consequence of a hot-plate orogenic style involving little crustal thickening, combined with "normal" juvenile magma additions. Progressive extraction of the heat-producing-elements into the mid-upper crust, where they remain below the erosional base level, resulted in anomalous thermal conditions that modulated the ongoing orogenic history. This may represent an important style in post-Archaean lithospheric behaviour.**

The thermal regime of the Earth is a primary control on its long-term evolution. Of particular interest are lateral and temporal changes in thermal regime and how these relate to processes like orogeny and crustal growth. Although globally crustal behaviour is thought by some to have changed around 3.0 to 2.5 Ga (e.g., Dhuime *et al.*, 2012), there is clearly a range of subsequent behaviour, for example, the differences between accretionary and collisional plate boundary orogenies. To investigate this range in behaviour data of appropriate scale is required so that significant differences are not obscured by, for example, averaging. Such data exists for Australian Proterozoic-aged terranes in the extensive, publicly available OZCHEM database maintained by Geoscience Australia (Figure 1a). In these terranes the felsic igneous rocks and the orogenic style both appear unusual. Indeed, large volumes of granite with high concentrations of the heat-producing-elements U, Th and K (and enriched incompatible element patterns in general, compared to other granitic datasets), intrude quasi-continuously throughout the Palaeo-Mesoproterozoic (c. 1880-1500 Ma; Figure 1b). At the continent-scale the Australian Proterozoic terranes have an average crustal heat production of 1.3 $\mu Wm^{-3}$—almost twice that of average Proterozoic crust (e.g., Jaupart and Mareschal, 2004)—based on known crustal thicknesses (Kennett *et al.,* 2011) and an average modern-day surface heat flow of 83 ± 18 $mWm^{-2}$ (Cull, 1982) to which the crust contributes 50-70 $mWm^{-2}$ (McLaren *et al*., 2003). Although Proterozoic Australia as a whole appears to be unusual thermally, considerable heterogeneity is observed. With the nature of the rocks and the volume of data available, we use the Australian Proterozoic case to investigate a potentially important style of post-Archaean crustal behaviour and growth.

## The North Australian Craton

The Geoscience Australia OZCHEM database contains whole-rock geochemical analyses of Australian rocks. For Proterozoic-aged granitic rocks (with $SiO_2 > 65\%$, following, for example, Kemp & Hawkesworth, 2004) there are 4997 individual whole-rock analyses that include U, Th and K data. We combined these data with available U-Pb geochronologic data from Geoscience Australia's OZCHRON database, published State Geological Survey reports and the literature. There were 3435 individual analyses for which ages were able to be assigned and these were used in this study. Our discussion focuses particularly on the extensive Proterozoic North Australian Craton (NAC, Myers *et al*., 1996; Figure 1a) as over 80% of the Australian Proterozoic analyses are from rocks within the NAC. We consider the NAC rocks to be representative of the range and variability observed among all Australian Proterozoic granites (see also Supplementary Figures).

Within the NAC there is considerable geochemical variation within and between the basement inliers (e.g., Supplementary Figure S2). Although we consider all NAC data here, we also note that the Mount Isa Inlier appears to be representative of the range and variability of granitic rocks observed throughout the NAC. Indeed, comparing all data from the NAC, all data from the Mount Isa Inlier, as well as the 1850-1880 Ma subsets of data from each group (Supplementary Figure S3) shows that the range and distribution of data from the Mount Isa Inlier closely approximate the data from all NAC terranes. This is at least in part because the age range and volume of data available are greater in the Mount Isa Inlier than in most other NAC terranes (Supplementary Figures S2, S3).

We first note that Figure 2a confirms that the NAC is more radioactive than the Palaeozoic granites of the Lachlan Fold Belt (LFB) as well as a global compilation of granites (Bea, 2012). However, Proterozoic granites from Norway (Slagstad, 2008) show a mixed distribution with a signature of both the lower-average global data and the higher-average Australian data. Moreover, in Australia different age components have rather different distributions, with a tendency for the granites to become more radioactive with time (Figure 2b). Interestingly, the oldest NAC granites (> 1850 Ma), of the so-called Barramundi Association (Etheridge *et al.*, 1987), show a similar range and distribution of heat-producing-elements to both the LFB and global datasets (compare Figure 2a and 2b). This observation suggests that the NAC may not have originally been unusual—having rather normal geochemistry around 1880-1850 Ma—but subsequently evolved to have a bigger range of composition, with an average that is more incompatible element-enriched (including more radioactive) than normal.

The key to this change appears to be the orogenic style, which is unusual in the Proterozoic terranes of the NAC. Following its assembly due to accretionary orogenic processes in Barramundi times (Cawood & Korsch, 2008), the NAC has largely evolved in an intraplate setting. The subsequent history of these terranes is characterized by (1) repeated tectonic reactivation (orogenesis and rifting), for example, > 300 My of orogenic activity interspersed with long-lived extensional tectonism in the Mount Isa Inlier (Cawood & Korsch, 2008; Betts *et al.,* 2006); (2) mainly high-temperature–low-pressure metamorphism, with average metamorphic pressures around 3-5 kbar (e.g., Rubenach, 1992; compilation in McLaren *et al.*, 2005); (3) non-linear orogenic systems with relatively large aspect ratios (Figure 1a); and (4) a general paucity of features associated with classic plate-margin orogeny, like sutures and granitoids of continental arc affinities (Wyborn *et al.,* 1992; Sheppard *et al.*, 2001; McLaren *et al.*, 2005). The currently exposed crustal level, as indicated by the pressures recorded by the rocks now at the Earth's surface, is shallow across most basement blocks (e.g., Scrimgeour & Sandiford, 1993; Bodorkos *et al.,* 1999), reflecting limited post-orogenic exhumation, particularly when compared to Proterozoic metamorphic belts elsewhere (e.g., Ketchum *et al.*, 1994; Knudsen 1996). This might also relate to an apparent first-order relationship between crustal thickness and Proterozoic-aged basement (Kennett *et al.,* 2011). Below, following a more detailed discussion of the magmatic rocks, we suggest that the exhumation level of the orogens is a key factor in establishing the unusual nature of NAC.

## The Origin of Australian Proterozoic Granites

To understand the significance of the magmatic rocks, the source material and the heat source must be identified. A series of recent papers (e.g., Dhuime *et al.,* 2012; Kemp *et al.,* 2009; Lancaster *et al.,* 2011; Nærra *et al.,* 2012) has demonstrated the benefit of combining oxygen, U-Pb and Hf isotopic studies of granitic zircons in constraining magmatic source regions. Indeed, LFB granites of both I- and S-type (Chappell & White, 1992) record isotopic evidence for mixed sources, with significant juvenile additions contributing to magmatism throughout the Palaeozoic (Kemp *et al.,* 2009). In contrast to previous Nd-isotope studies (Wyborn *et al.,* 1992), Hf-isotope data from granitic zircons in the Mount Isa Inlier (Griffin *et al.,* 2006) also points to juvenile mantle input into the granitic source over an extended period, similar to the LFB case (Kemp *et al.,* 2009). Thus (following for example Taylor & McLennan, 2009), a two-stage magmatic process is envisaged for the Australian Proterozoic terranes whereby (1) addition of a juvenile more-mafic source to the lower crust was followed by (2) melting (involving a lesser or greater contribution from pre-existing lower and upper crustal material) to generate granitic rocks that were then emplaced into the upper crust.

In this way we suggest juvenile additions from the mantle to the lower crust provided both heat and source material to generate the observed granitic suites. The first major addition occurred c. 1880-1850 Ma, but Hf data suggests these additions were ongoing (Griffin *et al.,* 2006). Indeed, the emplacement of juvenile basaltic material into the deep crust is an effective mechanism of producing intracrustal melts (Annen & Sparks, 2002), providing necessary thermal input. In terms of incompatible trace elements (including heat-producing-elements), the geochemistry of the resulting granitic rocks is a spectrum—something that is observed among the Australian rocks (Figure 2, Supplementary Figures S2, S4)—depending on the nature and proportion of pre-existing crustal rocks involved and the temperature and proportion of juvenile input. Moreover, areas in which melt zones are produced from the addition of juvenile material are susceptible to further melting (Annen & Sparks, 2002), potentially contributing to observed long-lived magmatic histories (Supplementary Figure S2). Thus, the long-term magmatic history of the Australian Proterozoic terranes cannot simply reflect reworking of older Proterozoic crust (c.f. McLaren *et al.,* 2005).

In terms of the proposed history of the NAC, with assembly by 1850 Ma followed by an intraplate evolution, the question arises why there should be ongoing juvenile inputs of, presumably, mantle-derived basaltic magmas. We suggest these inputs are endogenous to the lithospheric system, related to delamination associated with the removal of cumulate material from the lower crust/lithosphere that arose from differentiation of the juvenile material (Kay & Kay, 1993) and/or lithospheric thinning from crustal heating due to the burial under sedimentary basins of granites enriched in heat-producing-elements.

As highlighted by Kemp *et al.,* (2009), our understanding of the role of granitic magmatism in the growth of the continental crust has been somewhat obscured by a focus on an attempted genetic classification of granites that demands contrasting source regions for granites of differing geochemistry (i.e., I, S and A-type; White & Chappell, 1977). But recognition that all of the granites on which the classification scheme of White and Chappell (1977) is based record isotopic evidence for mixed sources (Kemp *et al.,* 2009), suggests inference on source composition from geochemistry alone is likely to be unsuccessful. We support this conclusion, noting that previous interpretations of Australian Proterozoic-aged granitic rocks may have been distracted by the I-S-A-type classification scheme.

## Understanding Magmatism and Orogenesis

The significance of the NAC orogens being exhumed only to a shallow level, as a consequence of the hot style of orogeny, is that granites intruded into the mid-upper crust were not able to be eroded. Thus their heat-producing-element enrichment was not dispersed. But why were these low-pressure orogens so hot? A distinction needs to be made between the first, *c.* 1880-1850 Ma, orogeny and subsequent orogenies, as it is likely that a feedback occurs when heat-producing-elements become trapped in the crustal system. That the c. 1880-1850 Ma granites have a heat-producing-element distribution rather similar to that of the LFB granites suggests the juvenile material added at this time was not unusual geochemically. Thus, fortuitous original enrichment is unlikely to be the cause of the subsequent lithospheric behaviour (c.f. McLaren *et al.,* 2005).

A more likely explanation is that this first orogeny was hotter for an exogenous reason, for example that the asthenosphere was hotter beneath this part of Columbia at that time. Following this first hot orogeny, subsequent magmatic and orogenic activity was also hot but now for endogenous reasons. That these orogens were hotter than normal plate-margin orogenic systems provided an efficient mechanism for extraction of the incompatible elements from the melt source. This hot-plate orogenic style, resulting from both the thermal-weakening effects of the heat-producing-element enriched material within the crust (McLaren *et al.,* 2005) as well as additional heat from juvenile additions, does not result in significant crustal thickening and consequently there is a general absence of high-pressure metamorphic rocks. Not only do the majority of pre-existing heat-producing-elements remain trapped in the crustal system, but any additional heat-producing-elements from new juvenile additions are also "trapped". This accounts for the granites showing a progressive increase in the range of recorded heat production with time, resulting in higher average heat production values for younger granitic rocks (Figure 2b). The efficient extraction of granitic melt, including the heat-producing-elements, from the lower crust to the upper crust during magmatism leaves the lower crust more residual and denser. This contributes isostatically to the enriched granites being less likely to be eroded. Thus, we interpret the long-term evolution of the NAC continental crust to reflect an intraplate geodynamic regime operating as a consequence of the “trapped” heat-producing-elements, and reflecting the repeated addition of heat and magma source material from the mantle.

## Discussion

Our model may represent an important style in the range of lithospheric behaviour in the post-Archaean. The hot-plate style of orogeny leads naturally to the trend to higher heat-producing granitic rocks with time as a result of both endogenous and exogeneous thermal and source inputs. There is no reason to suppose that anything other than “normal” juvenile additions to the lithosphere are involved, in contrast to exceptional additions of heat-producing elements invoked in most previous models.

That the magmatic and orogenic processes recorded in Australia – and the heat-producing-element enriched rocks that result – occurred elsewhere may be reflected in the record of sedimentary Uranium deposits known to be related to Proterozoic source rocks (Hazen *et al.,* 2009). Indeed we suggest that elsewhere on Earth, in the absence of the right combination of exogeneous and subsequent endogeneous drivers, slightly cooler Proterozoic orogenic systems meant that crustal thickening was greater than in the Australian orogens. Thus the heat-producing-elements were not so effectively trapped and were instead subject to erosion and dispersal. Indeed the fact that the various inliers of the NAC had different longevities—with Mt Isa being the longest-lived—may reflect the time at which the orogeny involved had become sufficiently cool for significant heat-producing element dispersal to begin, bringing orogenic activity to a halt.

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## FIGURE CAPTIONS

**Figure 1.** (a) Location of Australian Proterozoic-aged crustal blocks; in total Palaeo-Mesoproterozoic felsic igneous rocks within these terranes outcrop over an area of more than 100,000 km$^2$. Dashed lines delineate the WAC = West Australian Craton, SAC = South Australian Craton and NAC = North Australian Craton (nomenclature from Myers et al., 1996). MtP = Mount Painter Province, WBH = Willyama-Broken Hill Province, EGC = Eastern Gawler Craton, GC = Gawler Craton. The Tasman Fold Belt system extends eastward from the Tasman Line and includes the Lachlan Fold Belt, indicated in light stipple. (b) Age and calculated heat production (μWm$^{-3}$) data for granitic rocks of the North Australian Craton and for the Mount Isa Inlier. Note that throughout this manuscript we use the term granite *sensu lato*, for rocks with $SiO_2$ contents > 65% (see also Supplementary Discussion). Heat production is calculated for each rock at the time of its intrusion. We note that over 300 Ma (approximately the interval between the oldest and youngest Mount Isa granites, for example) calculated heat production would decrease by only around 5-6% due to natural radiogenic decay. -All geochemical data were sourced from the Geoscience Australia OZCHEM database (www.ga.gov.au) (see also Supplementary Figures).

**Figure 2.** (a) Calculated heat production (μWm$^{-3}$) for granitic rocks from Proterozoic-aged terranes in Norway (Slagstad, 2008); a compilation of global data that does not include Australian Proterozoic-aged granites (Bea, 2012); the Palaeozoic Lachlan Fold Belt of the Tasman Fold Belt system in eastern Australia (Chappell and White, 1992); and terranes of the North Australian Craton (NAC; here comprising the Arunta

Province, Coen Inlier, Georgetown Inlier, Mount Isa Inlier, Tennant Creek Block, McArthur Province, Arnhem Inlier, Halls Creek Inlier, Tanami Inlier and Pine Creek Inlier). (b) Calculated heat production of granites of different age groupings within the Mount Isa Inlier. In both (a) and (b) *n* indicates the number of individual analyses in each dataset. In both figures note that kernel curves, rather than histograms are used. They were calculated using an Epanechnikov kernel and a smoothing parameter of 0.2 (Wand and Jones, 1995; see also Supplementary Figures). In order to make their distribution more symmetric and thus easier for comparison—and because trace concentrations tend to show a log-normal distribution on frequency diagrams—data are shown here using a log-scale (following Ahrens, 1954). The area under the kernel curve is normalised to unity so that the y-axis is effectively a probability; heat production in the logarithm on the x-axis has units of $\mu Wm^{-3}$.

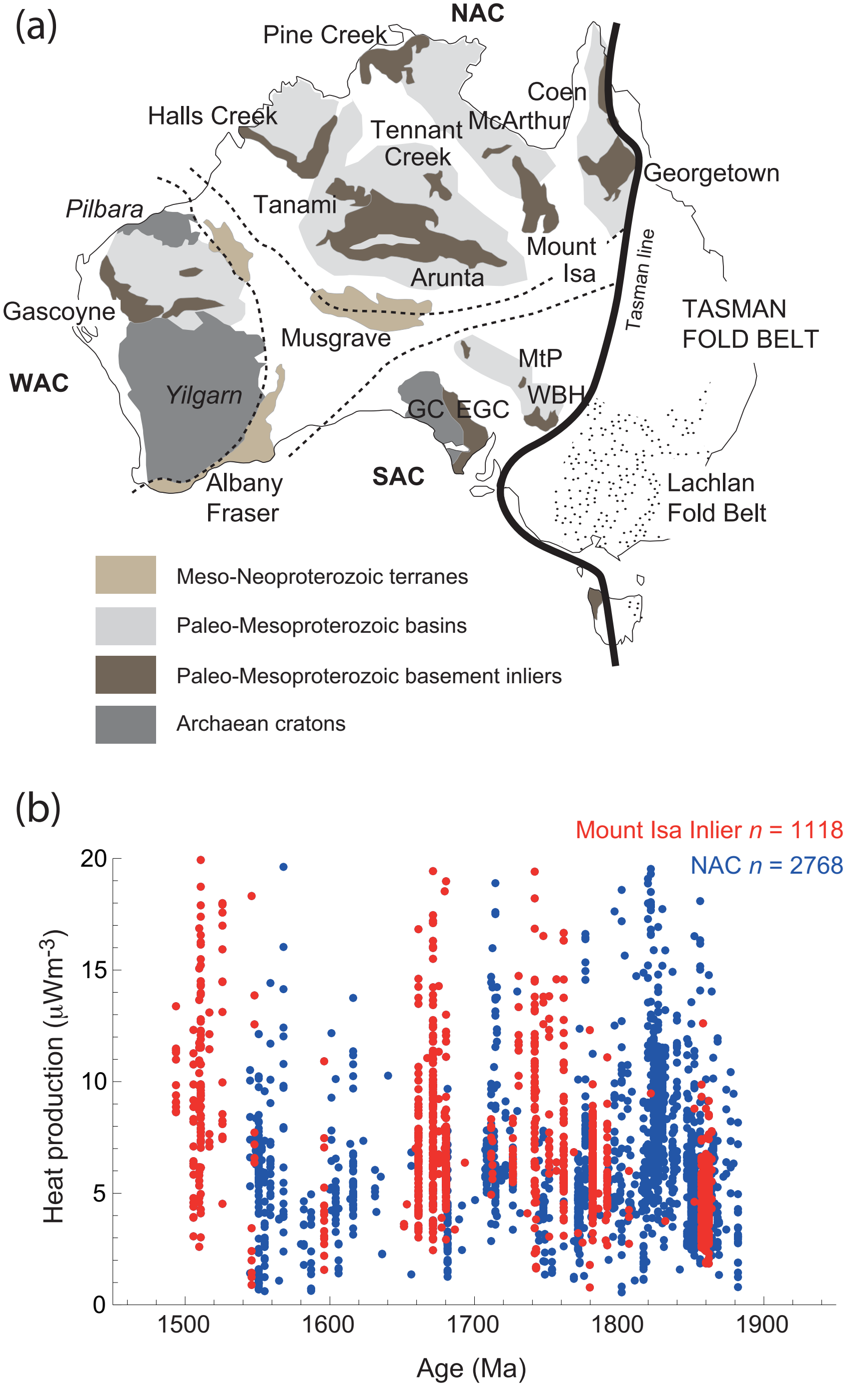
(a)
NAC
Pine Creek
Coen
Halls Creek
Tennant Creek
McArthur
Georgetown
Pilbara
Tanami
Mount Isa
Arunta
Tasman line
Gascoyne
TASMAN FOLD BELT
Musgrave
WAC
MtP
Yilgarn
WBH
GC
EGC
Lachlan Fold Belt
Albany Fraser
SAC
Meso-Neoproterozoic terranes
Paleo-Mesoproterozoic basins
Paleo-Mesoproterozoic basement inliers
Archaean cratons
(b)
Mount Isa Inlier n = 1118
NAC n = 2768
Heat production (μWm-3)
20
15
10
5
0
1500
1600
1700
1800
1900
Age (Ma)

Figure 1

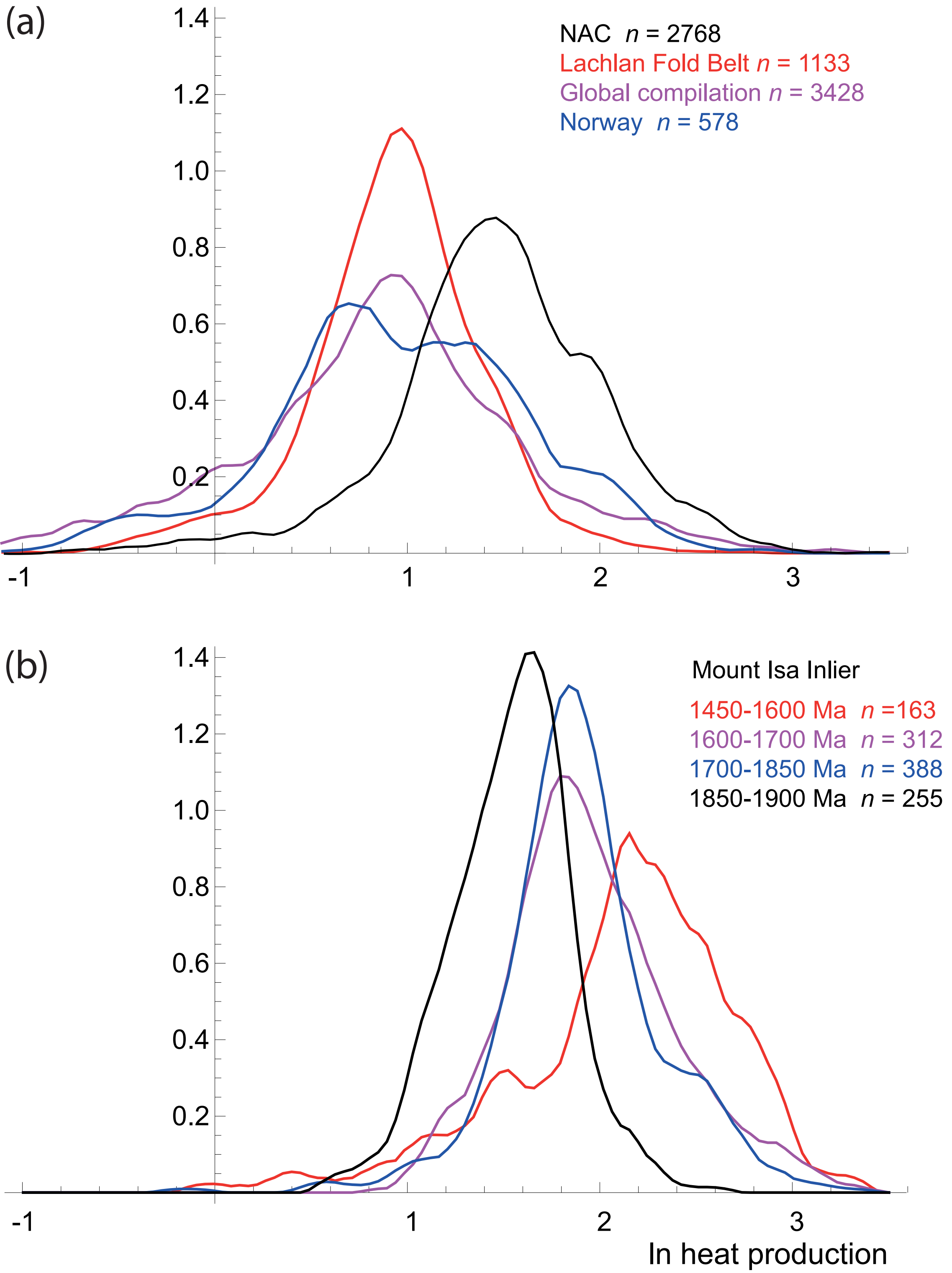
(a)
NAC n = 2768
Lachlan Fold Belt n = 1133
Global compilation n = 3428
Norway n = 578
1.4
1.2
1.0
0.8
0.6
0.4
0.2
-1
1
2
3
(b)
Mount Isa Inlier
1450-1600 Ma n =163
1600-1700 Ma n = 312
1700-1850 Ma n = 388
1850-1900 Ma n = 255
1.4
1.2
1.0
0.8
0.6
0.4
0.2
-1
1
2
3
ln heat production

Figure 2