Long-term consequences of the redistribution of heat producing elements within the continental crust: Australian examples

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Abstract

Steady-state lithospheric thermal regimes are sensitive to the heat supplied from the convective mantle and the heat generated internally by the decay of radioactive isotopes. The focus of this thesis is on the impact of change in the distribution of heat producing elements on lithospheric thermal regimes and on temperature dependent processes such as metamorphism, magmatism and deformation, with application to Proterozoic Australia.

In many regions of Australian Proterozoic crust, analysis of surface heat flow and heat production data suggests that crustal heat sources contribute around 50-70 mWm\(^{-2}\) to the lithospheric thermal budget, more than twice that normally expected for crust of this age. In these Proterozoic terranes granites and granite gneisses are extraordinarily enriched in the heat producing elements with calculated heat production for these rock types averaging 4.6 \(\mu\)Wm\(^{-3}\) when normalized by area of outcrop. This value is almost twice that of the average granite and is even more extraordinary given that the total area of outcropping granite on which it is based is in excess of 100,000 km\(^2\). This heat production appears to be strongly differentiated and concentrated in the upper 10 kilometres of the crust. This distribution is clearly a consequence of the processes that have shaped these regions of crust, such as deformation and magmatism, motivating an analysis of the time evolution of the distribution. Because lithospheric thermal regimes are sensitive to the presence and distribution of the heat producing elements, it is appropriate to ask (1) how these heat sources have impacted on the thermal, and hence tectonic history of these terranes through time, and (2) how the anomalous heat source distribution has been modified by these processes.

A simple parameterization which describes the distribution of heat sources using just two variables: \(q_c\), the total contribution from crustal sources, and \(h\), the length scale over which those heat sources are distributed, allows the thermal and mechanical effects of the presence and redistribution of crustal heat sources to be evaluated, and illustrated simply on the cartesian plane. Because this parameterization makes no assumption about the analytical form of the heat source distribution, it is ideal for investigating the long-term evolution of crustal heat sources through time as a consequence of various tectonic processes. The analysis presented in this thesis shows that the high concentrations of radiogenic heat sources present in many Australian Proterozoic terranes constitute an important, but previously unrecognized, source of thermal energy. Steady-state lithospheric thermal regimes and total lithospheric strength are highly sensitive to the presence of such high concentrations of heat sources and, importantly, to the way in which they are distributed. If heat source distributions are undifferentiated, and characterized by high values of \(h\), significant thermal weakening results. For example, for a value of \(q_c\) of 50 mWm\(^{-2}\), increasing the heat production length scale from 6 km to 12 km results in an increase in lower crustal temperatures of more than 100°C (for typical thermal conductivities) and a decrease in effective strength by a factor of two to three.

The observation that the thermal and mechanical state of a high \(q_c\) lithosphere is particularly sensitive to changes in the depth of the heat production has implications for thermal processes occurring on the scale of individual terranes. For example, the burial of granites enriched in the heat producing elements beneath an insulating sedimentary cover increases the heat production.
length scale and allows high geothermal gradients to be sustained in the upper crust, while at the same time limiting lower crustal melting. This observation contributes to current debate on the origins of high temperature-low pressure metamorphism, and seems appropriate to metamorphism in the Palaeo-Mesoproterozoic Mount Isa inlier. In this case, the burial of the high heat producing Sybella batholith beneath the Isa Superbasin is capable of generating steep upper crustal thermal gradients immediately prior to the ~ 1530 Ma Isan orogeny. These gradients are appropriate to the observed peak metamorphic conditions (600°C and 3-4 kbar), such that the Isan orogeny required no significant additional heat input. This model helps to account for the otherwise anomalous ~ 130 Ma delay between intrusion of the Sybella Batholith and metamorphism of the surrounding rocks, the absence of lower crustal syn-metamorphic magmatism and also the curious observation that metamorphism followed an extended phase of post-rift thermal subsidence. This result is significant as it may provide a mechanism for understanding the origins of high-temperature metamorphism in other terranes where conventional paradigms, such as the advection of heat from depth during magma emplacement, are not appropriate.

The sensitivity of the crust to the distribution of heat sources also has implications for crustal evolution on much longer time scales. Given that the primary crustal processes of magmatism, extensional and shortening deformation effect the redistribution of these heat sources they also impact on steady state thermal regimes and lithospheric strength, and hence the propensity of that crust to localize future tectonic activity. Because these primary tectonic processes are themselves sensitive to lithospheric thermal regimes and, therefore, the distribution of crustal heat sources, an important feedback system exists. This feedback has impacted profoundly on the long-term evolution of the crust in Australian Proterozoic terranes.

Both models and case examples show that the long-term history of these terranes reflects the progressive concentration of heat sources into the upper crust, largely through magmatism, but also through the coupling of deformation and surface processes. The trend to decreasing both $h$ and $q_c$ leads to long-term deep crustal cooling, an increase in total lithospheric strength and eventually to effective cratonization. The long-term cooling and strengthening trend is locally countered by the role of subsidence during basin formation which, through burial of heat producing elements in the existing crust and the accumulation of more heat production in insulating sediments, may help to localise subsequent deformation. Until $q_c$ and $h$ have been reduced sufficiently to minimize the thermal and mechanical impacts of those heat sources, the crust will remain susceptible to applied tectonic loads. This aspect of the feedback system provides a means for understanding long histories of tectonic reactivation and the timing of effective cratonization, particularly in intraplate settings. It also provides insight into the origin of the modern heat source distribution. This model is appropriate for both the Mount Isa and Mount Painter inliers and provides a novel insight into the long-term behaviour of the crust.