

Melting the crust – where is the heat?

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Granites don't appear to form randomly! Rather, they show a strong spatial and temporal association with tectonic phenomena that are, more often than not, related to plate boundary processes. Does this follow from any fundamental principle that precludes stable continental crust from developing the thermal regimes appropriate to granite production? For example, the sorts of thermal regimes required to melt the crust and/or underlying lithospheric mantle may well engender sufficient mechanical weakening that such crust is incapable of forming part of a “plate” (in the sense of a plate as a mechanical entity capable of acting as a stress guide over geological timescales). Thus any crust capable of generating significant quantities of granite might spontaneously localise a plate boundary. This notion is consistent with a temperature dependent lithospheric rheology. Thus, we might postulate that in-so-far-as plate tectonics requires the transmission of stress through continental interiors (witness contemporary Australia), plate tectonics precludes steady state thermal regimes appropriate to the generation of granites. Embedded in this is the possibility of a profound “tectonic feedback” that leads to the thermal (and, as we will see, geochemical) self-organization of the continental lithosphere [6], largely facilitated by granite genesis. To explore this hypothesis we need to understand more of the link between thermal regimes and granite genesis.

So, what supplies the heat in the modern crust? Basically we have two sources related to, on the one hand, deep convective processes and, on the other, internal heat production. In as much as the lithosphere forms a thermal boundary layer to mantle convection, thermal regimes in the continental interiors are a function of the vigour and form of convection in the deeper mantle as well as the thermal property (conductivity and heat production) structure of the lithosphere. Analysis of surface heat flow and heat production data indicates that typically about 2/3 of the heat that flows through the surface of the continents ($q_s \sim 65 \text{ mWm}^{-2}$) is derived from the radiogenic sources within the lithosphere [6]. The thermal regimes in the continental crust reflect not only to the amount of the internal heat production, which we term q_c , but also the way it is distributed with depth which can be represented by the characteristic depth of the heat production, h . The remarkably simple relationship :

$$T_{q_c} = \frac{q_c h}{k}$$

describes the potential Moho temperature contribution (T_{q_c}) provided by crustal heat production for a characteristic crustal thermal conductivity, k . Typical continental crust ($q_c \sim 45 \text{ mWm}^{-2}$, $h \sim 10 \text{ km}$, $k \sim 2.5 \text{ Wm}^{-1}\text{K}^{-1}$) gives $T_{q_c} \sim 180^\circ\text{C}$. The Moho is of course hotter than this due to mantle heat flow:

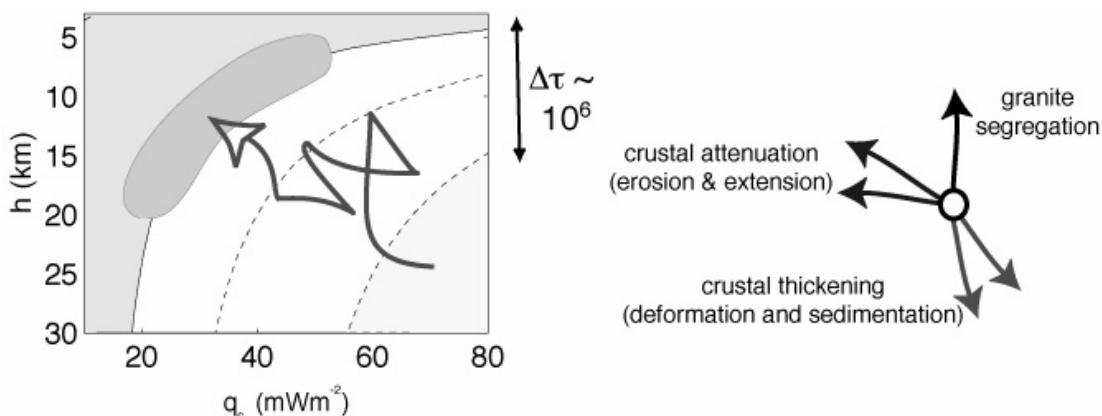
$$T_{q_m} = \frac{q_m z_c}{k}$$

For characteristic values ($q_m \sim 20 \text{ mWm}^{-2}$, $z_c = 40 \text{ kms}$) $T_{q_m} \sim 320^\circ\text{C}$, with $T_{\text{Moho}} (= T_{q_m} + T_{q_c}) \sim 500^\circ\text{C}$.

Intriguingly, because granites often host a significant fraction of the crustal complement of heat producing elements (HPEs), their generation and segregation must necessarily lead to changes in the thermal structure of the crust [6]. Consider a crust in which

half the complement of HPEs is carried by granites now lodged in the upper 10kms of the crust. Imagine these granites were derived from a source at depths between 30-40 kms depth from which the transported HPEs were extracted. The long-term change in Moho temperatures resulting from the segregation of such granites, is simply given by product of the transported heat production ($\sim 20 \text{ mWm}^{-2}$) and the change in depth ($\sim 30 \text{ kms}$) divided by the characteristic thermal conductivity. All other things being equal, the stable Moho temperature for this scenario was 240°C hotter prior to granite generation [7]! Importantly there would be no difference in the surface heat flow before or after the granite generation, because the crust contains the same total heat production (q_c), it is now just at much shallower levels!

The simple relationships can be illustrated in the plots of h versus q_c , which although rather naïve have the virtue of being able to illustrate the thermal response to a variety of tectonic processes and the potential coupling between granite generation and thermal and mechanical regimes in the continental lithosphere [6]. An important insight provided by the above analysis, is that for characteristic values of q_m , q_c and z_c , the only way of getting crustal melting ($T_{\text{Moho}} > \sim 850^\circ\text{C}$) is the unlikely scenario of having all the internal heat production at near Moho depths.



There is simply not enough heat in the normal crust to generate granites! So much we probably already know (but at least now we have a simple formalism for understanding it)! However, as we go back in time the effects of secular changes in the heat production assume considerable importance, such that we could imagine for the Archaean (when heat production rates of the crust were 2-3 times modern day rates, and hence q_c was much greater), the above arguments no longer hold. For example, burying highly radiogenic crust beneath thick piles of greenstone could easily generate deep crustal thermal regimes appropriate to crustal melting simply as a consequence of the change in depth of the heat production [5]! For the Pilbara we calculate an effective q_c of 80 mWm^{-2} during the mid-Archaean [1], providing this heat production averaged a depth of 20 kms then potential Moho temperatures of $>900^\circ\text{C}$ would prevail ($z_c \sim 40 \text{ kms}$) even for the low values of q_m ($\sim 20 \text{ mWm}^{-2}$) appropriate to the modern crust. An interesting corollary of this is that in order for such terranes to act as cratons (ie mechanically robust), there is very real imperative to achieve a ‘sensible’ HPE distribution. We see from the geological record that this was achieved by both solid-state and magmatic ascent of the structurally deeper felsic crust through the greenstone carapace producing the classic Archaean granite–greenstone ‘dome and keel’ architecture. As such, this structural style might be best viewed as a type of *geochemically-motivated* tectonics consistent with the crustal scale self-organization alluded to above.

Some large blocks of crust seem to have unusual concentrations of HPEs - a classic example being the Proterozoic of Australia where the available heat flow measurement suggest relative enrichment of HPEs by as much as a factor of two [3, 4]. For such crust it is conceivable that conditions close to granite melting can be achieved with relatively minor redistribution of the HPEs (see comments below).

So how do we get granites in the modern Earth! Given that there is simply not enough heat in the typical modern crust to generate granites, we must appeal to thermal transients. We may consider the source of these transients as potentially due to factors internal or external to the lithosphere. Two end-member scenarios are usually considered here, although it is likely that in real world scenarios there is considerable blurring between these. The first is one of crustal thickening in which we take a spatially “spread out” distribution of HPEs and concentrate them in a thickening pile simultaneously increasing the depth to the Moho. A crustal thickening by a factor of 1.5 leading to a factor of 1.5 increase in both q_c and h increases in T_{qc} by 2.25 and in T_{qm} by 1.5 (neglecting any corresponding change in q_m). Our model crust therefore has the potential of achieving Moho temperatures of $\sim 900^\circ\text{C}$.

Much of the thinking about this kind of process, is motivated by very simple kinematic models in which we take a column of crust, instantaneously deform it to a new state and consider its ensuing thermal evolution. In this scenario, the potential Moho temperature can only be achieved many 10^7 's of millions of years after the crustal thickening. In reality the flow of material (deformation) through orogenic systems is a lengthy and complicated process with strong thermo-mechanical coupling and, potentially, significant viscous dissipation of heat. It is quite possible that channels of high-temperature, low-viscosity material flow great distances and advect considerable heat in comparatively short periods of time, with the effect of greatly compromising many of the timescale arguments implicit in the simplistic kinematic model described above. Still, there is probably not quite the heat we need for widespread crustal melting in moderately thickened, ‘normal’ continental crust. On the other hand, thick piles of juvenile immature sediment, derived from the erosion of relatively HPE enriched upper crustal sources (such as Lachlan Foldbelt turbidites) do have the potential for generating significant melting if they undergo moderate tectonic thickening on the timescale of a few 10^7 's of millions of years.

The alternative is to provide for more efficient transport of mantle heat into the realm of crustal melting. This may be achieved by thinning the mantle lithosphere [10,11] - tantamount to increasing the mantle heat flow, or by advecting mafic magmas into the crust [8,9]. These processes are likely to be coupled, in which case they provide a very efficient way of elevating crustal thermal regimes for sustained periods of time, as evident in the Halls Creek zone [2]. The timescales and relationships between deformation and the expression of granitic magmatism might well be linked by the way in which the heat is advected into the crust [8,9].

Many of the arguments presented here are based on notions of ‘normal crust’ – for average crustal values of q_c we do not have enough heat production to generate granites without appealing to unrealistic amounts of crustal thickening. For many purposes the natural variation in crustal properties may be of more significance. Radiogenic bits of crust buried within orogenic zones may have fundamental impact on the thermal and mechanical evolution of those zones in ways that we still need to understand. If this is the case, then there is a necessity to get this heat production out of the deep orogenic system, in order to stabilise that crust, and clearly granites have provided a very effective way of doing this. *From a thermo-mechanical point of view*, the end product of the geochemical processing has left us with continental crust today which is largely well organised in the sense of facilitating plate tectonics. The way in which this has been achieved has probably changed through geological time, although granites have always played a key role.

Further elaboration of the ideas expressed herein can be found amongst the following papers.

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- [3] 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, eds Hillis, R.R. Muller, D., *Evolution and dynamics of the Australian Plate*, Geological Society of Australia, Special Publication, 22, 151-161.
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- [5] Sandiford, M., Van Kranendonk, M., Bodorkos, S., Conductive incubation and the origin of granite-greenstone dome and keel structure: the Eastern Pilbara Craton, Australia, submitted to *Tectonics*.
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- [11] Turner, S., Sandiford, M., Foden, J., 1992, Some geodynamic and compositional constraints on "post-orogenic" magmatism, *Geology*, 20, 931-934.