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Strain-heating as a mechanism for partial melting and UHT metamorphism in convergent orogens in view of temperature-dependent diffusivity and rheology

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Summary

We explored the importance of strain-heating in deep-crustal shear-zones for the production of leucogranites and high-temperature metamorphism in collisional orogens by constructing 1-d and 2-d numerical models of thermal evolution. These models include realistic values of temperature-dependent thermal diffusivity and rock rheology. We demonstrate that strain-heating can effectively raise temperatures to the crustal solidus, and in the absence of melt and other fluids, to UHT conditions. Temperature-dependent thermal diffusivity has also implications for the shape of the geotherm of the lithosphere.

Introduction

Processes within the continental lithosphere, such as partial melting and high-temperature metamorphism, are driven by the transfer of heat. In thickened collisional orogens, where evidence for heat advection by mantle-derived basaltic magmas is often lacking, the temperatures necessary to obtain partial melting and granulite or ultra-high temperature (UHT) metamorphism are difficult to achieve without a large amount of internal heat generation. Most published models rely on deep burial of crustal materials with high radiogenic heat production to generate the high temperatures necessary for partial melting in the middle crust. Instead, we explored strain-heating in deep-crustal shear zones as a potential mechanism for generating partial melting and, in the absence of liquids, UHT metamorphism. Accounting for the temperature-dependence of thermal diffusivity and rock rheology is key to producing realistic models for heat-production by mechanical deformation in the ductile regime of the crust.

Temperature-dependent thermal diffusivity and the crustal geotherm

New measurements of thermal diffusivity (*D*) for a granulite and a gneiss from the Bohemian Massif show that *D* is ~1.3 mm^2/s at 25 °C and as low as 0.4 mm^2/s at >600 °C. Combined with previous data for the thermal diffusivity of schists (Whittington et al., 2009), the data define an exponential thermal diffusivity function for metamorphic rocks. The decrease in *D* with increasing *T* results in model lithospheric geotherms which are straighter in comparison with geotherms calculated with the frequently-used constant *D* of 1 mm^2/s. A steady-state geotherm calculated for the Bohemian Massif based on the current thicknesses of the crust and lithospheric mantle and constant radiogenic heat production of 1.3 $\mu W/m^3$ throughout the crust is consistent with present-day surface heat flux of 50-70 mW/m^2.

Heat production by strain

Using recently published power-law parameters for rheology of crustal materials, we show that deformation of quartzite at strain-rate of $3 \cdot 10^{-13}$ s^{-1} produces >100 $\mu W/m^3$ at 550° C and ~7 $\mu W/m^3$ at 800° C. Deformation of a stronger clinopyroxenite at this strain-rate produces ~8 $\mu W/m^3$ even at 1050° C. These heat-production values greatly exceed the normal volumetric radiogenic heat production in upper-crustal rocks of 2-3 $\mu W/m^3$. The maximum heat production by strain-heating in the upper crust is limited by the brittle strength of rocks as expressed by Byerlee's law. When strain-heating is introduced in the form of a 3 km-thick shear-zone with quartz rheology at the depth of 35 km in a lithosphere with 70 km-thick crust and 60 km-thick lithospheric mantle, the schist solidus is reached by ~8 m.y. in the vicinity of the shear-zone deforming at the strain-rate of $3 \cdot 10^{-13}$ s^{-1}. With rheology of a clinopyroxenite, UHT metamorphic conditions are reached in ~40 m.y. after the initiation of strain-heating. Strain-heating in a shear-zone during unroofing of the crust produces isothermal decompression paths that are evident in mineral assemblages of some UHT terrains.

Two dimensional models that loosely replicate the exhumation of the Greater Himalaya crystallinites between the Main Central thrust and the South Tibetan detachment provide conditions commensurate with extensive partial melting in the zone between the two faults as well as an inverted metamorphic field gradient below the thrusting shear zone. The models reproduce ongoing partial melting in the Himalayan crust that is evident in seismic tomography (Caldwell et al., 2009; Nabelek et al., 2009) and the surface heat flux in southern Tibet (The Global Heat-Flow Database; http://www.heatflow.und.edu).

Conclusions

Strain-heating produces heat solely from mechanical deformation of the crust, which is ultimately a result of tectonic forces. Occurrence of leucogranites within crustal shear-zone systems and high strains seen in granulite and UHT terrains provide concrete evidence that deformation and heat production in the crust are coupled.

References

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