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HEAT TRANSFER BY FLUIDS IN GRANULITE METAMORPHISM;

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Granulite metamorphism represents the extremes of crustal conditions short of melting. These extreme conditions place important constraints upon models that can be used to explain the generation of granulites which we find exposed at the surface. In this short contribution we examine these constraints and discuss the role of fluids in granulite metamorphism, with special reference to the granulites of southern India.

Requirements of Granulite Metamorphism

Granulite metamorphism requires temperatures in excess of 700°C, and pressures are commonly recorded in exposed granulites indicating burial depths of 15 to 30 km. Nearly all examples of exposed granulite rocks contain at least some component of supracrustal rocks, including sediments, volcanics, or other rock units which formed at or near the Earth's surface (1). These granulites are now exposed on the surface of normal thickness crust (35 to 40 km). Thus, three components are required in any mechanism proposed to explain granulite metamorphism:

1) Transport of supracrustal rocks to 15-30 km;
2) Heating to 700°C or higher; and
3) Re-exposure at the surface of normal thickness crust.

Models for Regional Metamorphism

Models of regional metamorphism can be divided into two basic groups for the purpose of understanding granulite metamorphism: Monogenetic and Polygenetic models. In monogenetic models the transport of supracrustals to 15 to 30 km and the re-exposure at the surface are assumed to result from a single tectonic event. The commonly invoked mechanism invoked in this context is continental underthrusting and crustal thickening through which the supracrustals are transported to depth by underthrusting, and re-exposed by isostatic uplift and erosion of the thickened crust. The constraint that the exposed granulites are always underlain by 35 to 40 km of crust is inherent in this mechanism. In polygenetic models, transport to depth and re-exposure are assumed to result from different tectonic events. The supracrustals can be transported to depth either by underthrusting as in the monogenetic models, or by deep burial associated with multiple extensional crustal thinning events (isostatic considerations suggest that single events are unlikely to produce sedimentary basins much greater than 10 km, even under the most favorable assumptions). Re-exposure then results from an independent tectonic event, either a compressional event in which the granulites are overthrust onto a normal thickness crust, or through tectonic unroofing during extension, although the normal thickness crust constraint requires that this extension takes place in an overthickened crust.

We have so far ignored the second necessary component of granulite formation, the heating to 700°C or more. This component places important constraints upon heat transfer associated with granulite metamorphism. In all monogenetic models of granulite formation, and the polygenetic models which invoke tectonic unroofing during extension, a minimum of 35 to 40 km of crust beneath the granulites is required at the time of their heating and formation. As the granulite mineralogies commonly indicate burial depths of 15 to 30 km, they would have been formed roughly quarter to half-way down an overthickened crustal section. Taking a very simplistic view that the geothermal gradient is uniform throughout the crust, the Moho temperature would be expected to be two to four times the temperature at the depth of granulite formation: i.e., 700°C at the granulite formation depth implies Moho temperatures of 1400 to 2800°C. It is obviously over-simplistic to assume a uniform geothermal gradient throughout the crust, but as shown by Ashwal and others (1), if steady-state conductive conditions are assumed, it is impossible to devise a geotherm based upon realistic heat production values and thermal conductivities that decreases sufficiently with depth to allow temperatures of 700°C or more in the mid to upper crust without super-solidus temperatures in the lower crust. This constraint is removed if the granulites are formed in the lower crust and erosionally exposed following subsequent thrusting over crust of normal thickness. Alternatively, the steady-state conductive geotherm may be modified by the effects of convection in the crust.

Heat can be convected in the crust by the movement of fluids through the crust or by movement of the crust itself relative to the surface. We consider the latter form of convection first. General upward movement of the crust in isostatic response to erosion or tectonic unroofing has the effect of making the geotherm convex upward and raising temperature in the upper crust. Numerous examples of this effect are given by England and Thompson (2) for a variety of initial assumptions for monogenetic regional metamorphism models. However, although the required geotherm can be modelled by this mechanism, examination of pressure-temperature-time (PTt) paths for rocks initially buried in the mid to upper crust, shows that these rocks cool as a result of uplift and only pass through the granulite formation temperature field for models in which massive melting (super-solidus temperatures) is predicted in the lower crust. Maximum temperatures are attained at any specified horizon when the erosion rate is a minimum after crustal thickening, i.e., under steady-state conditions. Significantly increased temperatures at any specified horizon can only be generated by the upward convection of fluids through the crust, either magma or volatiles.

Models of magmatic convection of heat into the crust and the resulting metamorphism have been presented by Wells (3). These models show that the sustained addition of magma to the crust profoundly influences the geotherm, primarily at levels in the crust below the depth of magmatic accretion to the crust. Thus, the most efficient mode in which to produce granulites by this mechanism would be through intrusions into the upper crust, above the level at which the granulites are formed. Unfortunately these intrusions would be eroded before the granulites could be exposed, but some evidence of the passage of magmas through the granulites may be expected to remain. If no evidence exists for magmatism associated with metamorphism, heat transfer by volatiles may be a viable mechanism.

Advection of heat and matter by fluids during metamorphism has recently been studied by Bickle and McKenzie (4) for the case in which the rock is modelled as a porous medium, and heat transport is laterally homogeneous. At depth, however, it is likely that fluids flow through discrete fractures, and we have started to investigate metamorphism associated with fracture-controlled fluid-flow. Bodvarsson (5) has presented solutions for heating associated with water flowing through fractures for a limited set of flow conditions and single planar-fracture geometries. We use these solutions to estimate the effect of steady constant-temperature fluid-flow through a system of vertical planar-fractures in the crust. If vertical heat transfer in the rock medium is neglected, crustal temperatures are dominated by the temperature of the ascending fluid, which is of the form:

$$T = T_o \operatorname{erfc}\{A(d-z)\}$$

where T_o is the temperature of the base of the crust and the temperature at which the fluid enters the fracture, erfc{} is the complementary error function, d is the crustal thickness, z is depth, and A is a constant, defined by the flow rate, the ratio of fluid to rock thermal properties, and the time since the flow started. Preliminary calculations suggest that, for water, very modest flow rates (of the order of 0.1 g/s per m of horizontal fracture length) can significantly modify the geotherm, and that flows sustained over time periods of 1 ka to 1 Ma, depending upon fracture spacing, can produce temperatures compatible with granulite metamorphism in the mid to upper crust without requiring melting in the lower crust. More complete numerical studies by Hoisch (6) support these results and conclusion.

Granulites of Southern India

Summaries of the geology of the Southern Indian Shield (7, 8) suggest that granulite metamorphism in the southern portion of this shield was associated with a late Archean and/or early Proterozoic mobile belt in which the crust was thickened by compressional deformation.

There is abundant evidence for CO_2-K metasomatism throughout the shield, and we tentatively suggest that fluid-flow associated with this metasomatism was the primary agent of heat transport for the granulite metamorphism. Definition of a plate-tectonic regime associated with this deformation/metamorphism even is controversial, but it seems likely that compression and fluids for metasomatism/metamorphism were associated with early Proterozoic subduction.

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References

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