Earth science

Modelling mantle temperatures during the Archaean

from E. G. Nisbet

IN a recent paper[1] in *Geophysical Research Letters*, Jarvis and Campbell have attempted to resolve the apparent contradiction between the eruption temperatures of Archaean (older than 2.5×10^9 yr) magmas and the temperatures recorded in old continental metamorphic rocks. Thus, some komatiites (magnesium-rich Archaean lavas formed in the mantle) seem to have eruption temperatures in excess of 1,650°C (ref.2), whereas some metamorphic assemblages[3-5] preserved in granulitic rocks formed deep in Archaean continents seem to imply that, in some places at least, the heat flux into the base of the continents was approximately the same as it is today, and that the mantle temperature was not much hotter than the current 1,350–1,400°C.

Jarvis and Campbell have constructed a numerical model of whole-mantle convection and found that mantle temperatures at least 200°C more than exist at present lead to a highly disordered form of convection in which the horizontal thermal boundary layers are thinned to about 30 km and become highly unstable. Random portions of the cold surface layer would break off and fall into the interior and the continental crust could not survive. As there is good field evidence that large stable areas of continents have existed since early Archaean time, the implication of the Jarvis and Campbell model is that the Archaean mantle must have been cool enough — possibly only 100°C hotter than today — to avoid such disorder.

How, then, can the high eruption temperatures of the komatiites be accounted for? Jarvis and Campbell appeal to the only possible source in a whole-mantle convection model — the lower thermal boundary layer at the core–mantle boundary.

They suggest that komatiites were derived from hot plumes rising from instabilities of this layer, the hot parcels of mantle beginning to melt at about 450 km below the surface as they cross the solidus, and then reaching high degrees of partial melt before eruption. They go on to explain the 'cool' metamorphic evidence by suggesting that the recorded temperature profiles come from rocks formed near Archaean subduction zones where geothermal gradients were low. Thus their model manages to accomodate the metamorphic data but at the price of banishing the komatiites to the infernal regions.

The model is interesting and may well have much truth in it, but is based on some questionable assumptions. One is that viscosity was spatially uniform but exponentially dependent on the mean temperature of the convection layer. No attempt is made to investigate the effects of possible chemical stratification in the mantle[6] on the viscosity and solidus: if a refractory dunitic uppermost mantle existed, or if a magma ocean lay in the lower part of the upper mantle, the variation in viscosity would be sharply discontinuous. Furthermore, since komatiites are abundant in the Archaean geological record and may have been the parent liquid to mid-ocean ridge lavas, the required number of plumes rising from the core–mantle boundary may be unreasonably large.

England and Bickle[3] have recently tackled the problem by investigating the 'cool' metamorphic gradients and then exploring their consequences; they point out that the relationship between the eruptive temperatures of komatiites and the temperature of the mantle is poorly understood. If the continents were indeed cool, then the heat flux of the surface of the Earth was probably out of equilibrium with the generation of internal heat (which was three to four times greater then than now). They point out that if temperatures at the base of the continental crust were more than a couple of hundred degrees higher than they are now, the Archaean lithosphere would not have been able to support the mountain heights that are implied by the metamorphic pressure data. They also conclude that the forces driving orogenesis in the Archaean were comparable in magnitude to modern forces — around $5\times10^{12}\,\mathrm{N\,m^{-1}}$.

Both these models favour mantle temperatures close to modern values. What of the 'hot' point of view? A different starting point is to assume, simplistically, that the komatiites really do reflect typical mantle conditions and to investigate the consequences. What if the mid-ocean ridges were fed by a komatiite parent liquid[7,8]? A komatiite oceanic crust overlying a hot olivine-rich lithosphere and upper asthenosphere would be much hotter at comparable depth than modern oceanic plate, and thinner on subduction. Compared with present conditions, such a system of plate tectonics might allow a greater proportion of the total surface heat flux to be carried by the creation and destruction of plates, the plates being thinner, hotter and faster-moving.

Extrapolation of the available information about the densities of olivine and of magnesium liquids suggests that, at depth, olivine would float in komatiite liquid[6]. If so, a magma zone may have existed at depth. Such chemical stratification would have a major control on heat transfer within the mantle and it is possible that to some extent the heat flux depended on the mechanisms controlling ascent of magma from this molten zone. Perhaps the oceanic plates dissipated much heat but the continents were relatively cool. Much depends on the continental lithosphere which may have been less thick than today but perhaps more refractory. The distribution of radioactive elements within the crust and mantle may also have been different.

All this modelling depends on field evidence which is complex and difficult to interpret. The maximum MgO content (and hence eruptive temperature) of komatiite liquids is not well known although 32 per cent (1,650°C or more) is commonly assumed. Metamorphic 'geotherms' do not represent thermal equilibrium of an isochronous column of rock, even if they are derived from rock assemblages which somehow managed to approach thermodynamic equilibrium. For this reason, England and Bickle's study of the controls on pressure, not temperature, is most interesting. At what stage would continents overthickened by deformation simply spread out?

Isostasy comes in here. Erosion also controls continental thickness, which has probably always been much as today[9]. But was there water in the ocean and what was its level? Were the mid-ocean ridges so high that they protruded, or even tipped out the water onto the continents? And were the Archaean oceans deeper?

The depths of the oceans and the heat flux problem have wide significance. It is possible that some of the first progenotes inhabited early Archaean hydrothermal systems in the same way that archaebacteria occupy black smokers on modern mid-ocean ridges. Thus the nature of the ridges — their chemical composition and temperature, the water depth, the amount of heat dissipated in hydrothermal systems close to the ridge and hence the extent of interaction between new oceanic crust and seawater — are all of major interest in considering the origin of the biosphere and the controls on its evolution in time. Indeed, by stabilizing temperatures and allowing for water in the oceans, life may have exerted a profound control on the Earth's tectonic regime. □

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