layer seems to be necessary to produce a significant heat flux from the core demanded by any dynamo mechanism, but an additional composition change cannot be excluded. A large impact at the Earth's surface could not affect the composition of the layer and it is difficult to see how it could substantially affect the thermal regime.

In all physically realistic situations the addition of some noise process (random or otherwise) must intrude to influence the evolution of the system. Work in my laboratory[18] shows that the addition of three types of stochastic processes (gaussian, flicker and brown noise) enriches the field evolution and can predict accurately palaeomagnetic reversal behaviour. Irregularities either in material properties, physical or chemical processes or in fluid dynamical turbulence could provide an adequate source of noice. It seems much more probable that this external stimulation by a random component is internal to the core and is not caused by an extraterrestrial event. □

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Geophysics

Mantle mixing still a mystery

from Dan McKenzie

PRINCIPALLY because of the work of isotope geochemists, it is now clear that the Earth's mantle contains certain regions of significantly different Sm/Nd and Rb/Sr ratios, which have probably existed for at least 1,000 million years. All oceanic islands are produced from such regions. If their geometry and size distribution were known they could be used as strong constraints on the history of mantle circulation. The difficulty lies in deciphering the geological observations, a problem addressed by two papers, one recently published in *Nature*[1] and the other on page 317 of this issue[2].

The most impressive feature of volcanic rocks dredged from the ocean floor is not their heterogeneity but their homogeneity: they are almost all classified by petrologists as one particular type of basalt. This uniformity extends to the isotope ratios $^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$, which are measures of the average Rb/Sr and Sm/Nd ratios over periods comparable to the age of the Earth. The most obvious way in which such a homogeneous source could be produced is by mixing in the dust cloud from which the Earth formed. But all geochemists who have worked on the problem agree that the homogeneity did not originate in this way, because the source shows clear signs of depletion of Nd and Sr at some later time in its evolution. This depletion event is generally believed to be the formation of the continents, whose average age is about 2,000 million years. The standard type of geochemical modelling, with fluxes between uniform reservoirs, accounts for the observations[3-5], but provides no clue as to how the homogenization occurs.

Because the depletion is widely believed[1] to occur at island arcs, and therefore to be very localized, the homogenization must be both fast and efficient. Recent studies of two-dimensional convection, reviewed by Allegre and Turcotte[1], show that vigorous two-dimensional time-dependent convection can (just) achieve the necessary homogenization. However, if the Rayleigh number of the convection is too small, time-dependent flow does not occur and the stirring occurs only within one convective cell. Efficient stirring occurs over larger regions only when the flow is time-dependent. Then the particle paths are not stream lines, so the description of such stirring as stream-line mixing[1] may be misleading. Recent work on lead isotopes[6] suggests that the stirring time may be as short as 500 million years, considerably less than the estimates from two-dimensional convection. Because any cook knows how much more effective three-dimensional stirring is than two-dimensional, such a difference is not surprising as mantle convection is certainly three-dimensional.

Vigorous stirring will not by itself produce a homogenous mantle, but one in which inhomogeneities are reduced to thinner and thinner streaks. Only when their size is less than a few tens of centimetres will solid-state diffusion produce true mixing. The question which has dominated discussions of mantle heterogeneity for the past 10 years is whether it is possible to extract the necessary volumes of basalt to make oceanic islands from thin streaks of enriched mantle without involving the thicker depleted streaks in between? That this argument is not settled is clear from the two recent *Nature* papers[1,2], which take opposite sides on this question. In my view the only way of doing so is through understanding the physical processes involved in the generation of melt and its movement to the surface. Although such studies are progressing rapidly, they are not yet able to resolve the question. Until it is resolved it is unclear whether melt extraction acts to increase[1] or to decrease[2] the magnitude of the isotope anomaly on some length scale. Mathematically, the mapping of the mantle heterogeneities into surface anomalies by melting is non-linear and the functional form is unknown.

Why not avoid all these problems by studying pieces of the mantle which are now at the surface, as Allegre and Turcotte propose? The difficulty with this approach is that nasty things happen to the mantle on its way to the surface. The mantle starts its journey at a temperature sufficient to produce melting if it were at atmospheric pressure, and is also likely to be strongly deformed on its way up. My first attempt[7] to study mantle structures directly was motivated by the crystal geometries within pieces of mantle brought up with diamonds. It later became clear that these fabrics would last less than half an hour under mantle conditions. The observed structures were related to the extraction event, not to the much slower mantle circulation. The most obvious method to demonstrate that the pyroxene bands in peridotite[1] are long-lived features, and are not formed by melting and deformation during uplift and emplacement into the crust, is to measure the isotope ratios in the different layers. If the observed ratios correlate with the banding, some estimate of its age could be made. Unfortunately, no such correlation is observed[1], probably because of the movement of small quantities of volatile-rich melt into the peridotite which transported Sr and Nd.

It is disappointing that all attempts to determine the geometry of mantle heterogeneities have been equally inconclusive. As is so often the case, the problem is important but appears to be at present unanswerable. □

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