The lifetimes of ancient chemical heterogeneities in the mantle and their implications for the evolution of mantle convection

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Because the Rb–Sr and U–Pb isotope pairs each include at least one element prone to alteration, and only few Lu–Hf data exist for both ancient and modern mantle-derived rocks, the assessment of mantle heterogeneity early in Earth history rests solely on the Sm-Nd isotope system. Combined Nd isotope compositions and Sm and Nd concentrations are currently available for some 500 Archaean samples of potential mantle origin comprising the 3.9–3.8, 3.5, 3.2, 2.9, and 2.7 Ga age groups. For the modern mantle, Sm and Nd concentrations are not systematically available for all Nd isotope analyses. Here we consider *c.* 1350 ocean island, mid-ocean ridge, and back-arc basin basalts. Because the practice of considering fields tends to overemphasize the importance of rogue points in otherwise unpopulated areas of geochemical plots, the compiled data sets for the different age groups have been handled as 2D histograms in coordinates of $\varepsilon_{Nd}(T)$ and $^{147}Sm/^{144}Nd$ (Fig. 1).The density diagrams (contoured at 33, 66, and 90%) of the compiled data for the 2.7 Ga and present-day age groups display overall positive correlation between $\varepsilon_{Nd}(T)$ and $^{147}Sm/^{144}Nd$ for positive $\varepsilon_{Nd}(T)$ values (Figs. 1a-b). By contrast, pre-2.7 Ga age groups show little or no correlation between $^{147}Sm/^{144}Nd$ and positive $\varepsilon_{Nd}(T)$, the latter being rather constant at around +1 to +2 despite a large variation in $^{147}Sm/^{144}Nd$ (Figs. 1c-f). The range of

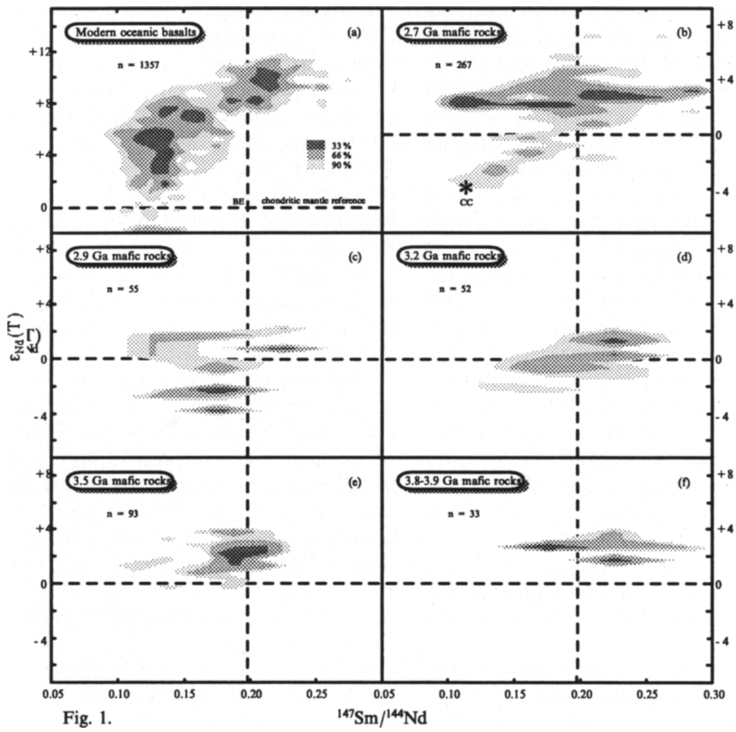

FIG. 1.

$^{147}Sm/^{144}Nd$ (0.10-0.30) is nearly the same for all age groups attesting to similar melting processes in the Archaean and modern mantle. For the 2.9, 3.2, and 3.5 Ga age groups (Fig. 1c-e), the most depleted samples ($^{147}Sm/^{144}Nd$ > 0.23) do not appear on the diagrams as they constitute less than 10% of the respective data sets. Within the observed range of Sm/Nd ratios, $\varepsilon_{Nd}(T)$ changes by ten units (from +2 to +12) for modern basalts (Fig. 1a) but by only one unit (from +2 to +3) for Late Archaean basalts (Fig. 1b) and half a unit for pre-2.7 Ga basalts (Figs. 1c-f), of which the latter is within analytical uncertainty.

While the 3.9–3.8 Ga age group is characterized exclusively by positive $\varepsilon_{Nd}(T)$ (Fig. 1f), the 3.5 Ga age group displays $\varepsilon_{Nd}(T)$ gradually approximating chondritic values (Fig. 1e) and the pre-3.5 Ga age groups exhibit negative $\varepsilon_{Nd}(T)$ (Figs. 1a-d). The latter is accompanied to still larger extents by Sm/Nd ratios approaching crustal values thus providing evidence of crustal contamination or recycling in the mantle. The absence of a crustal component for the pre-3.2 Ga age groups (Figs. 1e-f) implies that either crustal recycling was not an important process in the Eartly Archaean, or the recycled material was juvenile.

It is argued that because variations in ε_{Nd} must reflect compositional variations in the mantle as well as the time intervals during which individual domains remained isolated, the correlation of the Sm/Nd ratio with positive ε_{Nd} for Late Archaean and modern mantle suggests that variations in the former primarily reflect Sm/Nd variations in the mantle and not fractionation during melting.

A quantitative assessment of ancient mantle heterogeneities is currently best achieved on rocks of Late Archaean age, because by far the largest Sm-Nd isotopic data base for the Archaean is for this age group (Figs. 1b-f). The Nd isotope and Sm/Nd systematics of the 2.7 Ga old basalts suggest that the lifetime of chemical heterogeneities in the Late Archaean was a factor of ten shorter than today (Blichert-Toft and Albarède, 1994). The even smaller variation in ε_{Nd} values for pre-2.7 Ga basalts indicates yet shorter survival times in the Early Archaean. The result that chemical heterogeneities appear to have been obliterated faster by about one order of magnitude in the Archaean compared with the modern mantle has important consequences for the nature of the convectional regime of the Earth's mantle in the past.

The survival time of heterogeneities in the mantle is a function of two competing processes: (i) heterogeneity creation by mantle melting (fractionation) and (ii) destruction by convective stirring (mixing). Because the range in Sm/Nd ratios is the same in both the Archaean and the modern mantle, (i) can be ruled out. If, therefore, the survival time of chemical heterogeneities was shorter in the Archaean than today, it is likely that so was also the mixing time. For single-layer laminar flow convection, Hoffman and McKenzie (1985) found that the 'doubling time', which is the time it takes to stretch a surface by a factor of two, is proportional to Ra-1/2. Assuming that the doubling time can be scaled by the lifetime of chemical heterogeneities, it follows that the Rayleigh number of the late Archaean mantle probably was larger than that of the present-day mantle by two orders of magnitude. Survival time of heterogeneities an order of magnitude longer today than in the Archaean suggests convective movements ten times greater in the Archaean than at present. This can be ascribed to the higher thermal regime prevailing early in Earth history. Because more vigorous mantle convection is likely to lead to higher plate velocities, modern plate tectonics may not be an adequate analog for the Archaean.

Geophysical models of global thermal evolution indicating that the Earth's interior was significantly hotter in the past than at present, and the occurrence of komatiites exclusively in the Archaean geological record, are consistent with the Sm-Nd systematics presented above. Recently, additional supportive evidence for more vigorous convection in the Archaean mantle is also provided by hydrodynamic theory (Iberall *et al.*, 1993). Specifically, for early Earth conditions near 3.9 Ga, a confirmatory estimate of the surface heat of nearly 10 times the current heat flux and a heat loss of about 8 times that of today is inferred on the basis of a variety of physico-chemical heterogeneous processes in the mantle and core, modern plate tectonics, and a combination of hydrological and meteorological process cycles on the surface of the Earth.

Preliminary investigations of Proterozoic mantle-derived rocks, especially the 2.1-1.9 Ga age group, show both well-defined correlations between Sm/Nd and positive $\varepsilon_{Nd}(T)$ and variations in ε_{Nd} intermediate to those of the Late Archaean and the present. This suggests that mantle convective velocity has decreased gradually with time as Earth has cooled off progressively.

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