Hf-Nd isotopic covariance in the crust and mantle and constraints on the evolution of the depleted mantle

J. Vervoort
P. J. Patchett
Department of Geosciences, University of Arizona, Tucson, Arizona, 85721, USA

J. Blichert-Toft
F. Albarède
Ecole Normale Supérieure de Lyon, UMR CNRS 5570, 69364 Lyon Cedex 7, France

It has long been recognized that Lu-Hf and Sm-Nd isotope systems behave analogously during most magmatic processes but the details of Hf-Nd isotopic behaviour in the major crust and mantle reservoirs have not been fully demonstrated. How Hf and Nd isotopes behave in the depleted mantle through time, for example, has been uncertain because of the apparent different Hf-Nd variations in MORBs and OIBs and the potential for decoupling these systems in a number of important mantle (e.g. Salters and Hart, 1991) and crustal (e.g. Patchett *et al.*, 1984; Vervoort and Patchett, 1996) environments. New Hf-Nd results in combination with existing data, allow us to make some first-order observations of Hf-Nd behaviour in some of the Earth's major reservoirs.

Oceanic Basalts. Hf-Nd data for plot along an array defined by the line $\varepsilon_{Hf} = 1.3\ \varepsilon_{Nd} + 3.1$. The OIB array is indistinguishable from the array for all oceanic basalts (including MORBs and IABs) of $\varepsilon_{Hf} = 1.3\ \varepsilon_{Nd} + 3.6$.

Crustal Samples. Muds and shales, recent to Archaean, plot along an array $\varepsilon_{Hf} = 1.4\ \varepsilon_{Nd} + 2.9$, similar to that for OIBs and all ocean basalts. Sands and sandstones are more scattered and plot along a steeper array ($\varepsilon_{Hf} = 1.8\ \varepsilon_{Nd} + 2.5$) due to the less radiogenic Hf character in some sands. This 'zircon effect' occurs in some sands derived from older crustal sources where the Hf in the sands is dominated by zircons less radiogenic than the Sm-Nd in the bulk rock.

All whole-rock data. All terrestrial whole-rock Hf and Nd data define a remarkably coherent array of $\varepsilon_{Hf} = 1.4\ \varepsilon_{Nd} + 2.9$ (Fig. 1). Mn crusts and pelagic red clays, some peridotite xenoliths, and a few sandstones with extreme zircon effects plot outside of the main array and are not included in this regression. This array contains diverse samples of wide-ranging compositions and ages. The close similarity of the Hf-Nd arrays for continental crust (as defined by muds) and the mantle (as defined by all oceanic basalt data) indicates no large-scale decoupling of Hf and Nd between crust and mantle. This tight Hf-Nd covariation may also argue for the efficacy of crust to mantle recycling in modulating Hf-Nd behaviour in the silicate Earth.

With this background, we report new whole-rock Hf-Nd isotope data for 1) mantle-derived rocks, mid-Archaean to Mesozoic in age and 2) early Archaean gneisses from West Greenland. Hf and Nd isotopic compositions are well correlated in the juvenile rocks, corresponding to $\varepsilon_{Hf} = 1.4\ \varepsilon_{Nd} + 2.1$, and plot well within the collective Hf-Nd array of terrestrial samples ($\varepsilon_{Hf} = 1.4\ \varepsilon_{Nd} + 3.1$). The early Archaean Greenland gneisses, in contrast, have an extreme range in ε_{Nd} values (−4.4 to +4.2; Bennett *et al.*, 1993) while corresponding ε_{Hf} values are more restricted and entirely positive (0 to +3.4) resulting in a Hf-Nd array for these rocks ($\varepsilon_{Hf} = -0.1\ \varepsilon_{Nd} + 2.3$) quite different from that defined by other terrestrial samples. This Nd isotopic heterogeneity is not a result of extreme depletions and enrichments in the early Earth, but from disturbances in the Sm-Nd isotope system of these rocks.

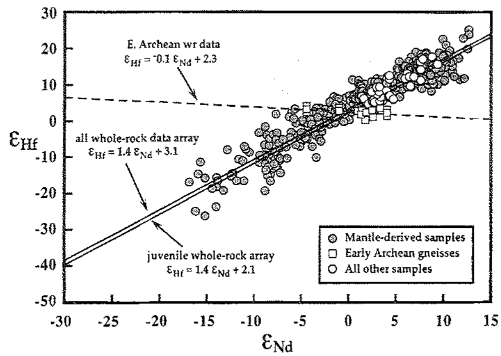

FIG. 1. Initial ε_{Hf} and ε_{Nd} values of early Archaean gneisses, mantle-derived samples Archaean to present, in comparison to all other whole rock samples.

Based on the strong Hf-Nd correlation, we would expect Hf and Nd isotopic records of depleted mantle evolution to be identical, and this is the case from 3.5 Ga to present. Both records show a near-linear increase in maximum initial ε_{Hf} and ε_{Nd} values from 2.7 Ga to present, and a period from 3.5 to 2.7 Ga where there is no discernible change in maximum ε values. Although Hf data show that extreme positive and negative ε_{Nd} values are not real, they do verify lower positive ε values for the early Archaean samples around $\varepsilon_{Hf} = +3.5$ and $\varepsilon_{Nd} = +2.5$. Thus the isotopic record still requires a depletion of the early Archaean mantle ($f_{Lu/Hf} = 0.43$; $f_{Sm/Nd} = 0.25$), significantly higher than the time-integrated rate for today's depleted mantle ($f_{Lu/Hf} = 0.16$; $f_{Sm/Nd} = 0.10$). This discrepancy necessitates a period of adjustment in the depleted mantle between the early and late Archaean (Fig. 2).

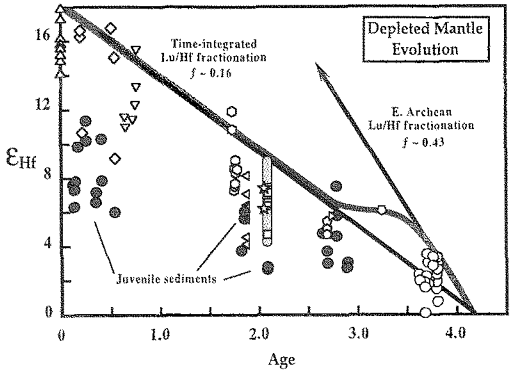

FIG. 2. Initial ε_{Hf} values for mantle-derived samples with ages 3.8 Ga to present.

One reason the issue of crustal growth has remained unresolved after more than 20 years of debate is that Hf-Nd isotopes of Archaean mantle-derived rocks constrain the development of the depleted mantle but only indirectly the growth of the continental crust. The Hf-Nd data presented here are consistent with either an Armstrong (1981) 'No-Growth' model that proposes present-day volumes of continental crust in the early Earth, or more gradualistic models of crustal growth. However, we find that a 'No-Growth' model is difficult to reconcile with the lack of isotopic (no verified negative ε_{Hf} and ε_{Nd} values in the oldest rocks) and physical (few rocks older than 3.5 Ga and a paucity of pre-4.0 Ga zircons) evidence. Rather, we suggest that the enriched reservoir in the early Archaean was a mafic, oceanic-like crust that was recycled to the deep mantle where it was sequestered for several hundred million years (e.g. Chase and Patchett, 1988), explaining the lack of negative ε_{Hf} and ε_{Nd} signatures in early Archaean crustal rocks. Collision and 'subduction' of mafic microplates resulted in the generation of small amounts of evolved tonalite-trondhjemite crust. This more 'continental-like' crust was preferentially preserved due to its increased buoyancy resulting in the progressive growth of sialic crust, but it was not until the middle Archaean (~3.5 Ga) that the more destructive processes in the early Earth had abated to the point where crust survival began to greatly outpace destruction. An important aspect of crustal growth and evolution, therefore, may be in the transformation of the enriched reservoir from being predominantly mafic in the early Earth to becoming progressively more sialic through time.

References

Armstrong, R.L. (1981) *Phil. Trans. Royal Soc. London*, **A301**, 443–72.

Bennett, V.C., Nutman, A.P. and McCulloch, M.T. (1993) *Earth Planet. Sci. Lett.*, **119**, 299–317.

Chase, C.G. and Patchett, P.J. (1988) *Earth Planet. Sci. Lett.*, **91**, 66–73.

Patchett, P.J., White, W.M., Feldmann, H., Kielinczuk, S. and Hofmann, A.W. (1984) *Earth Planet. Sci. Lett.*, **69**, 365–78.

Salters, V.J.M. and Hart, S.R. (1991) *Earth Planet. Sci. Lett.*, **104**, 364–80.

Vervoort, J.D. and Patchett, P.J. (1996) *Geochim. Cosmochim. Acta*, **60**, 3717–33.