Stable isotope evidence for Earth's raw materials

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Introduction

Variations in abundances of stable, nonradiogenic isotopes in natural materials may be used to study provenance of those materials or processes involved in their formation. In dealing with Earths mantle, the variations of interest include those which occur within the mantle, those which occur between mantle and other terrestrial reservoirs, and those which occur between the Earth and other solar system bodies. The last of these may shed light on chemical compositions of inaccessible regions of the mantle.Two examples are discussed here: (a) oxygen isotopes, which serve as tracers of recycled crustal material and provide stringent tests of two- or multi-component models of terrestrial accretion, and (b) potassium isotopes, which severely constrain processes for depletion of moderately volatile elements in the whole Earth.

Oxygen Isotopes in Mantle Nodules

Oxygen isotope fractionation factors among major phases in the upper mantle are small (mostly <0.5‰ in $\delta^{18}O$), but not totally negligible. Unaltered mantle-derived MORB reflects these small variations in their source. Subsequent interaction with seawater, over a range of temperatures from 0–300°C introduces large oxygen isotope variations, which result in both higher-$\delta^{18}O$ (low temperature) and lower-$\delta^{18}O$ values in the 'weathered' or hydrothermally altered sea-floor. Return of these materials to the mantle does not erase these isotopic heterogeneities, so that they may be subsequently observed in high-^{18}O and low-^{18}O eclogites in kimberlite nodules (e.g., Neal *et al.*, 1990).

Comparison of the oxygen isotopic composition of the Earth with that of potential building blocks (as represented by meteorites and their components) requires use of the three-isotope method (Clayton, 1993), which distinguishes between fractionation processes and mixtures of distinct components. Fig. 1 shows isotopic compositions of plausible raw materials for the inner planets: ordinary chondrites (O), type-3 carbonaceous chondrites — volatile-poor (V), and type-1 carbonaceous chondrites — volatile-rich (I). Fig. 2 shows the compositions of Earth and Mars (represented by SNC meteorites) within the triangle defined by the primitive components in Fig. 1. It is clear that no two-component model can account for the chemical and isotopic compositions of these planets. Furthermore, the content of Cl-like material cannot be more than a few percent, and appears

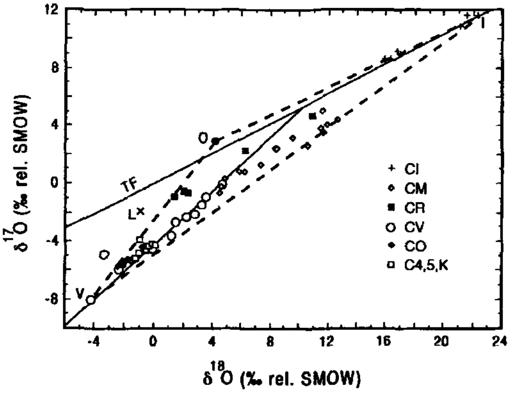

FIG. 1. Oxygen isotopic compositions of primitive meteorites. Compositions of differentiated bodies lie within the triangle bounded by O (ordinary chondrites), I (C1 chondrites), and V (C3 chondrites).

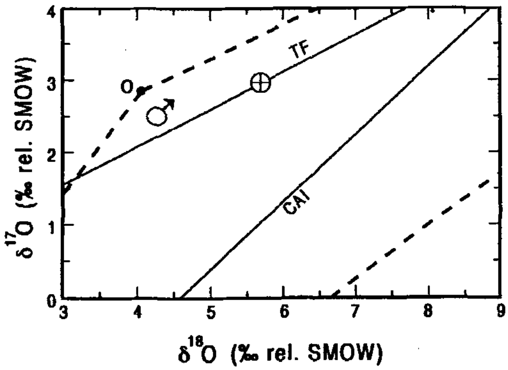

FIG. 2. Oxygen isotopic compositions of Earth and Mars (SNC) in relation to primitive components from Fig. 1.

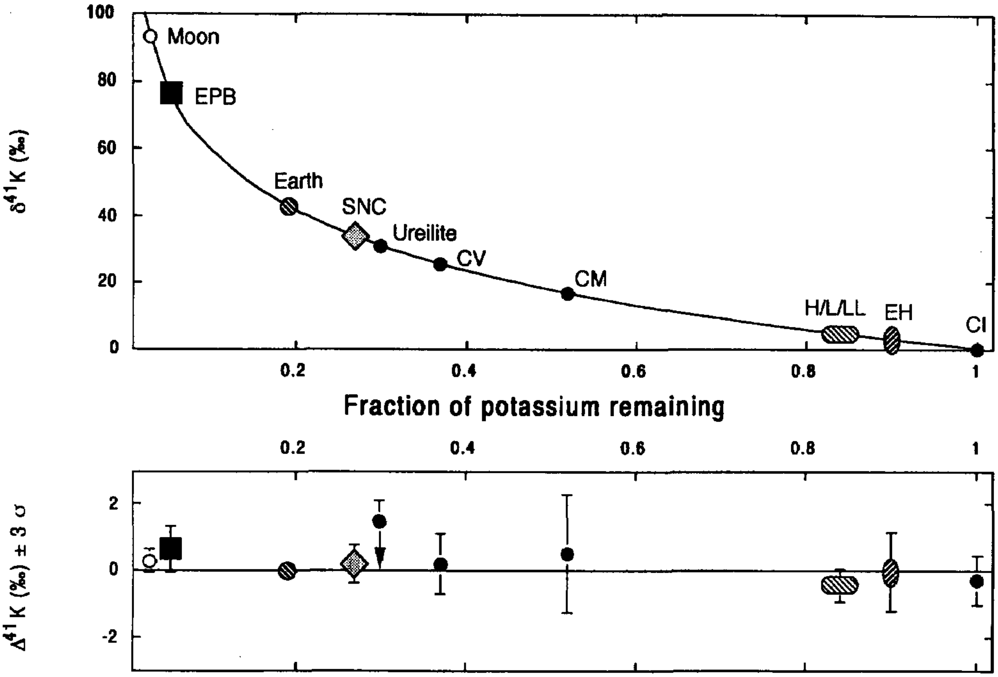

FIG. 3. Upper panel shows potassium isotopic compositions expected for various solar system bodies on the basis of kinetic isotope effects due to volatilization. Lower panel shows observed isotopic compositions; note 10-fold expansion of scale.

to be greater in Earth than in Mars, in contrast to the requirements for two-component models.

The exact coincidence of Earth-Moon and enstatite meteorites is remarkable, and probably reflects isotopic homogenization (on some scale) in the inner solar system. This homogenization was incomplete at the accretion distance of Mars and beyond.

Potassium Isotope Fractionation

Evidence from ratios of volatile/refractory incompatible lithophile elements on Earth shows that the planet as a whole is depleted in moderately volatile elements, such as K, Rb, Pb, S, etc. This depletion is part of a cosmochemical pattern which includes Mars (SNC), the Moon, and other achondrite parent bodies (HED, ureilites). Volatile element depletion might be accomplished by partial vaporization of such elements from dust grains, planetesimals or whole planets, or by incomplete condensation from a hot gas. Partial vaporization should manifest itself by a large kinetic isotope effect, as has been observed for Mg and Si in refractory inclusions in meteorites. We have shown (Humayun and Clayton, 1993, 1994) that intra-planet isotopic fractionation of potassium $^{41}K/^{39}K$ ratios) is negligible for Earth and Moon, so that a well-defined planetary composition can be determined. In a comparison of potassium isotopic compositions of Earth, Moon, and achondrites (all strongly potassium-depleted) with that of ordinary and carbonaceous chondrites (little or no potassium depletion), we find no difference in $\delta^{41}K$, within an uncertainty of ±0.5‰ (3σ). The fractionation effects expected for partial volatilization are on the order of 40–90‰ (Fig. 3). It is concluded that the major volatile element depletion of these planets did not result from partial vaporization of previously condensed elements.

References

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