

5. Pendry, J. B. *J. Phys. A: Math. Gen.* **16**, 2161–2171 (1983).
6. Rego, L. G. C. & Kirichenko, G. *Phys. Rev. B* **59**, 13080 (1999).
7. Krive, I. V. & Mucciolo, E. R. *Phys. Rev. B* **60**, 1429–1432 (1999).
8. Blencowe, M. P. & Vitelli, V. *Phys. Rev. A* **62**, 052104 (2000).
9. Shannon, C. E. *Bell Syst. Tech. J.* **27**, 379–423 (1948).
10. Caves, C. M. & Drummond, P. D. *Rev. Mod. Phys.* **66**, 481–537 (1994).
11. Blencowe, M. P. *Phys. Rep.* **395**, 159–222 (2004).
12. Brassard, G. *Nature Phys.* **1**, 2–4 (2005).

EARTH SCIENCE

Isotopic hide and seek

Francis Albarède

Isotopes formed by the decay of radioactive nuclei provide evidence of how Earth was shaped in its infancy. But some decay products seem to be hidden — a finding that will revitalize a debate about Earth's interior.

It is thought that Earth formed, along with the rest of the Solar System, from the gravitational collapse of a huge cloud of gas. But what were the processes that turned the resulting ball of rubble into a planet endowed with a metallic liquid core, a thick viscous mantle and a thin continental crust? Some clues may be found by measuring the abundance of neodymium isotopes in volcanic rocks, as reported by Boyet and Carlson in *Earth and Planetary Science Letters*¹. Their results illuminate the early dynamics of Earth's interior and provide fresh insight into the structure and flow of the modern mantle.

Many short-lived radioactive elements were created in the events that accompanied the formation of the Solar System. These elements — or rather, the isotopically distinctive products of their radioactive decay — provide clues about the processes involved in planetary accretion and development. In the final stages of Earth's formation, differentiation processes distributed its constituent minerals and metals between the core, mantle and crust. This resulted in the separation of radioactive nuclides from the products of their decay, so that isotope compositions of the daughter elements in modern-day minerals attest to the separation of vapour, melts and solid phases in the newborn planet.

For example, samarium (Sm) decays to produce neodymium (Nd); both of these elements are found in mantle silicates. Variations of neodymium-isotope abundances in terrestrial rocks are useful for dating melt segregation in the mantle. Most earth scientists are familiar with the decay of ¹⁴⁷Sm into ¹⁴³Nd, a process with a half-life of 106 billion years. This decay is used as a chronometer and as a tracer of material exchange between mantle and crust. But with such a long half-life it cannot provide a detailed picture of the dawn of geological times. In contrast, the much shorter half-life of ¹⁴⁶Sm decay to ¹⁴²Nd (103 million years) is comparable to the timescale of early planetary processes and so is well suited to investigating the dynamics of newborn Earth.

So far, the ¹⁴⁶Sm–¹⁴²Nd chronometer has found its most valuable application in the study

of magma oceans — envelopes of liquid silicate that hug newborn planets. The abundances of ¹⁴²Nd in 3.8-billion-year-old rocks from Isua in Greenland are higher than those in chondrite meteorites, which are made from the same raw materials as Earth and the other rocky planets. Samarium and neodymium are 'refractory' elements, which survived the harsh conditions found in the newborn Solar System. Their relative proportions in Earth must therefore be the same as for chondrites. The 'excess' of ¹⁴²Nd, compared with chondrites, in the Isua basaltic rocks is evidence of a very early melting event (the formation of magma oceans) that concentrated ¹⁴²Nd in certain regions of the newly created mantle^{2,3}.

The modern terrestrial mantle and continental crust also display excesses of ¹⁴²Nd compared with chondrites. This geochemical feature can only be explained if the mantle is the solid residue of an ancient slurry. To balance the books, the excess of ¹⁴²Nd in these regions must be paired with a deficit in another complementary material that is derived from the liquid part of the slurry. But this ¹⁴²Nd-deficient material is conspicuously missing from the geological record. Boyet and Carlson have previously argued⁴ that this component probably took the form of a primordial crust, which sank down to the core–mantle boundary very early in Earth's history. The case for a missing reservoir, distinct from the familiar mantle, has also been made based on the abundances of the heavier neodymium isotope ¹⁴³Nd in Archaean rocks⁵ (which are more than 2.7 billion years old) and of hafnium in oceanic basalts⁶. But the ¹⁴²Nd anomalies raise an additional useful point — that the absent material was segregated in the lower mantle during the first tens of millions of years of Earth's history.

The quest for the hidden reservoir commenced with studies on oceanic basalts derived from deep mantle material⁷. But now Boyet and Carlson¹ present high-precision ¹⁴²Nd abundance data from carbonatites and diamond-bearing kimberlites — volcanic rocks that are thought most probably to originate from the deepest parts of the mantle. They report that none of these rocks shows a deviation of ¹⁴²Nd

abundances from the modern terrestrial value. This suggests that the rocks do not originate from a ¹⁴²Nd-deficient reservoir or, at the very least, that the contribution of such deep-seated material is not detectable.

The authors' review different interpretations of their data. They first examine the possibility that Earth's composition may not be chondritic; this could be true if atomic nuclei weren't created in a uniform distribution throughout the nebula from which the Solar System formed. A recent paper⁸ suggests that at least one process of nucleosynthesis in supernovae could lead to uneven isotopic abundances of some elements. But the isotopic distributions of nearly all the elements are the same in other planets, which makes it very difficult to justify non-chondritic abundances of samarium and neodymium for Earth.

So, if the neodymium isotope compositions of magmas reflect those of their source mantle, the conclusion from Boyet and Carlson's data is inescapable: some lower-mantle material with a ¹⁴²Nd-deficit exists, untapped by deep magmas and separate from the convective flow field of the upper mantle. This ¹⁴²Nd-deficient material may be locked up in the so-called D'' layer of the lower mantle, which sits on top of the core–mantle boundary. Or perhaps it resides in a deep reservoir resembling the abyssal layer that is proposed to exist at a depth of about 1,600 kilometres⁹, although this layer has so far evaded detection¹⁰. Of course, it could simply be that the kimberlites and carbonatites analysed by Boyet and Carlson were contaminated on their way to Earth's surface, masking the modest ¹⁴²Nd deficit inherited from their source region⁷.

Several models for the structure and dynamics of the mantle have been proposed over the years, including the theory that two separate mantle layers exist, each with its own convection patterns. This theory seemed inconsistent with emerging seismic evidence and went out of favour. But thanks to Boyet and Carlson's studies¹, layered mantle convection may now be knocking at the back door, as this could explain why deep reservoirs have become segregated from upper mantle regions. The authors have revitalized this fundamental debate — and the arguments look set to continue for years to come.

Francis Albarède is at Ecole Normale Supérieure de Lyon, 69007 Lyon, France.
e-mail: albarède@ens-lyon.fr

1. Boyet, M. & Carlson, R. W. *Earth Planet. Sci. Lett.* **250**, 254–268 (2006).
2. Boyet, M. *et al.* *Earth Planet. Sci. Lett.* **214**, 427–442 (2003).
3. Caro, C. *et al.* *Nature* **423**, 428–432 (2003).
4. Boyet, M. & Carlson, R. W. *Science* **309**, 576–581 (2005).
5. Chase, C. G. & Patchett, P. J. *Earth Planet. Sci. Lett.* **91**, 66–72 (1988).
6. Blichert-Toft, J. & Albarède, F. *Earth Planet. Sci. Lett.* **148**, 243–258 (1997).
7. Boyet, M., Garcia, M. O., Plick, R. & Albarède, F. *Geophys. Res. Lett.* **32**, L04306 (2005).
8. Andreassen, R. & Sharma, M. *Science* doi:10.1126/science.1131708 (2006).
9. Kellogg, L. H., Hager, B. H. & Van der Hilst, R. D. *Science* **283**, 1881–1884 (1999).
10. Vidale, J. E. *et al.* *Geophys. Res. Lett.* **28**, 859–862 (2001).