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EARTH SCIENCE

Extraordinary world

The isotopic compositions of objects that formed early in the evolution of the Solar System have been found to be similar to Earth's composition — overturning notions of our planet's chemical distinctiveness. SEE LETTERS P.394 & P.399

JAMES M. D. DAY

Classes of meteorites called chondrites formed from material in the solar nebula — the cloud of gas and dust from which the planets also formed — and have not subsequently undergone substantial mineralogical or geological changes[1]. Earth's bulk composition, including its metallic core and silicate mantle and crust, should be the same as that of the bulk Solar System, and would therefore be expected to correspond to chondrite-meteorite compositions. This idea was cast into doubt in 2005 by the spectacular finding[2] that terrestrial materials have elevated abundances of neodymium-142 (^{142}Nd) compared with ordinary or carbonaceous chondrite meteorites, implying that Earth's accessible regions cannot have a chondritic composition. Burkhardt *et al.*[3] (page 394) and Bouvier and Boyet[4] (page 399) now reassess this matter by reporting high-precision analyses of isotopes of neodymium and samarium (Sm) in a variety of materials from the early Solar System. Their findings reaffirm that Earth's composition is chondritic.

Nature has gifted us with a spectacular diversity of stable isotopes and of isotopes formed through radioactive decay, thus allowing us to place precise constraints on Earth's composition. For example, the ratio of the abundance of ^{142}Nd to that of ^{144}Nd partly reflects the decay of ^{146}Sm to ^{142}Nd; ^{146}Sm is a now-extinct isotope that had a half-life of 103 million years[5]. Today's accessible terrestrial mantle has a ^{142}Nd/^{144}Nd ratio greater than that of ordinary and carbonaceous chondrites, which are thought to be the building blocks of the planets in the Solar System. A 'missing reservoir' of terrestrial material has been invoked to explain the difference. This reservoir has a lower ^{142}Nd/^{144}Nd ratio than have chondrites, and must have been isolated from the accessible Earth within the first 20 million to 30 million years of terrestrial formation[2].

Various models have been proposed to explain the location of the missing reservoir — for example, perhaps it is isolated in the deepest parts of Earth[2], or formed an early crust that was lost to space during massive planetary collisions[6]. The existence of such a reservoir would have profound implications for terrestrial evolution and habitability, because the reservoir would also contain a large fraction of the radioactive, heat-producing elements (uranium, thorium and potassium) and therefore would fundamentally affect Earth's heat budget[7].

An alternative possibility is that the discrepancy between Earth and chondrites was caused by isotopic variations imparted during the formation of the Solar System. Our Solar System is composed of elements inherited from extinct stars and supernovae that seeded different proportions of isotopes into different parts of the early solar nebula, leading to isotopic compositions in chondrites that are distinct from that of the present-day Earth. For example, ^{142}Nd is formed in stars by the slow process (s-process), a particular type of nucleosynthetic process in which neutrons are captured by atomic nuclei at a relatively pedestrian pace. The other isotopes of neodymium are formed either by the s-process or in 'core-collapse' supernovae by rapid neutron capture (the r-process).

Samarium isotopes also show composition variations associated with the s- and r-processes, and so, by combining analyses of samarium and neodymium isotopes, geochemists have a powerful tool for understanding the isotopic compositions inherited from stars and supernovae. By measuring samarium and neodymium isotopes at high precision in chondrites, Burkhardt *et al.* show that the materials that formed Earth were enriched in neodymium formed by the s-process.

Taking a different approach, Bouvier and Boyet measured the isotopic composition of calcium–aluminium inclusions — the earliest objects to have condensed from the solar nebula and therefore the oldest solid objects in the Solar System. They find that plots of the isotopic compositions of these inclusions,

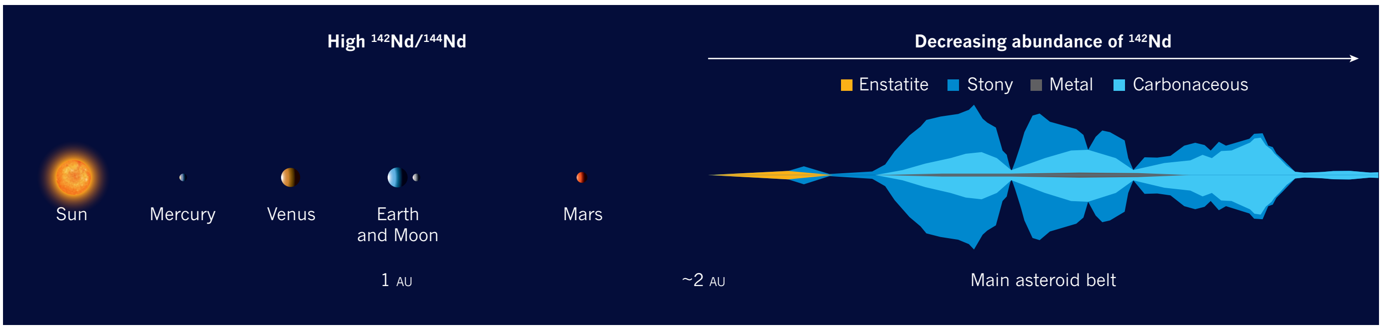

Figure 1 | An isotopically heterogeneous Solar System. Evidence that Earth has a higher abundance of neodymium-142 (^{142}Nd) than do two classes of meteorite (ordinary and carbonaceous chondrites) suggests that the Solar System inherited an uneven distribution of isotopes from stars and supernovae during its formation. Burkhardt *et al.*[3] and Bouvier and Boyet[4] measured ^{142}Nd abundances in early Solar System objects whose compositions broadly correlate with those of three types of main-belt asteroid that have surfaces similar to enstatite chondrites, stony chondrites or carbonaceous chondrites. Taking into account the distribution of asteroids and planets, the results imply that the abundance of ^{142}Nd decreases with distance from the Sun. Like Earth and the Moon, Mars has a high ^{142}Nd/^{144}Nd ratio compared with that of chondrites[8]. Distances from the Sun are in astronomical units (1 AU is 150 million kilometres) and are shown to scale, but planetary-body sizes are not to scale. The distribution of asteroids in the main belt is shown as an exaggerated cross-section; the distribution of metal asteroids, which have surfaces similar to those of iron meteorites, is shown for completeness. (Adapted from ref. 11.)

and of some enstatite chondrites (a rare form of meteorite), pass straight through the isotopic composition of modern Earth's accessible mantle. This implies that nucleosynthetic variations explain the distinctions between some chondrite groups and Earth. Remarkably, using two distinct approaches, both studies come to the same conclusion: after corrections for nucleosynthetic effects, Earth must have chondritic abundances of samarium and neodymium, and, by association, also of uranium, thorium, potassium and some other elements.

Even so, Earth remains extraordinary. Enstatite chondrites and calcium–aluminium inclusions cannot have formed Earth; they might partly overlap isotopically with our planet, but they are either too depleted in key elements, including volatile elements, or too chemically reduced to explain the terrestrial composition. Conversely, carbonaceous and ordinary chondrites are too depleted in ^{142}Nd (ref. 3). Moreover, chondrites and their components are unlikely to be representative of the materials that formed Earth because the materials that fed the formation of the inner planets no longer exist, having been processed within Mercury, Venus, Earth, the Moon or Mars. Instead, the formation of the Solar System might have been the result of 'cosmic cookery', in which stars and supernovae sprinkled variable isotopic compositions into the mix, akin to a chef seasoning a dish before serving it.

Burkhardt *et al.* and Bouvier and Boyet propose that the relative abundance of ^{142}Nd decreases with distance from the Sun (Fig. 1), and that this reflects either variable processing of dust from the solar nebula or distinct compositions of material sprinkled from star and supernova sources into the solar nebula over time. Further high-precision measurements of Martian meteorites[8] could help to validate these proposals: if the authors are correct, then such meteorites would be slightly deficient in ^{142}Nd compared with Earth. If Mercurian or Venusian meteorites can be found, then they would be expected to be enriched in ^{142}Nd compared with Earth, allowing stringent constraints to be defined for an isotopically heterogeneous, and possibly radially stratified, Solar System.

The latest results have major implications for our understanding of Earth's evolution. Earlier theories of a modern terrestrial mantle with a high ^{142}Nd/^{144}Nd ratio — dubbed a supra-chondritic Earth — have led to models that interpret lavas with primitive noble-gas and lead isotope compositions as coming from one of the most ancient accessible mantle reservoirs[9]. If Earth actually has a chondritic Sm/Nd ratio[3,4], then the missing reservoir hypothesized in previous studies[2,6,7,9] never existed. Alternatively, the 'primitive' isotopic variations measured in some lavas reflect the complex assimilation of ancient crustal materials into magmas formed by partial melting of Earth's mantle[10]. ■

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1. Anders, E. & Grevesse, N. *Geochim. Cosmochim. Acta* **53,** 197–214 (1989).
2. Boyet, M. & Carlson, R. W. *Science* **309,** 576–581 (2005).
3. Burkhardt, C. *et al. Nature* **537,** 394–398 (2016).
4. Bouvier, A. & Boyet, M. *Nature* **537,** 399–402 (2016).
5. Meissner, F., Schmidt-Ott, W.-D. & Ziegeler, L. *Z. Phys. A* **327,** 171–174 (1987).
6. Campbell, I. H. & O'Neill, H. St C. *Nature* **483,** 553–558 (2012).
7. Jellinek, A. M. & Jackson, M. G. *Nature Geosci.* **8,** 587–593 (2015).
8. Caro, G., Bourdon, B., Halliday, A. N. & Quitté, G. *Nature* **452,** 336–339 (2008).
9. Jackson, M. G. *et al. Nature* **466,** 853–856 (2010).
10. Day, J. M. D. *Chem. Geol.* **440,** 91–100 (2016).
11. DeMeo, F. E. & Carry, B. *Nature* **505,** 629–634 (2014).

EVOLUTION

Teenage tetrapods

Bone analysis of aquatic tetrapods from around the time when these four-limbed vertebrates began to move onto land reveals that the large specimens were only juveniles, raising questions about how these animals developed. See Letter p.408

NADIA B. FRÖBISCH

One of the most fascinating topics in vertebrate evolution is the transition of finned fish to four-limbed tetrapods. This transition involved changes to many aspects of the biology of our fish ancestors, including their respiration, waste removal and skeletal system[1]. The evolution of the limb, which eventually led to our own arms and legs, was a prerequisite for tetrapods' conquest of the land and ability to evolve the amazing variety of body forms and means of locomotion observed in both extinct and modern vertebrates. Given the pivotal role of this move onto land, the anatomical transformations involved have been a major focus of research, not only in palaeontological studies, but also in studies of evolutionary developmental biology and the relationship between anatomical structures and their function[2,3]. A paper on page 408 by Sanchez *et al.*[4] reveals insights into growth patterns of the early tetrapod *Acanthostega*. The results will provide a deeper understanding of the development and evolution of our four-legged forerunners.

Although many advances have been made in understanding the evolutionary transition from fish to tetrapod, a key piece of the puzzle has remained elusive — how did the earliest tetrapods grow? The process by which an organism develops from the fertilized egg to

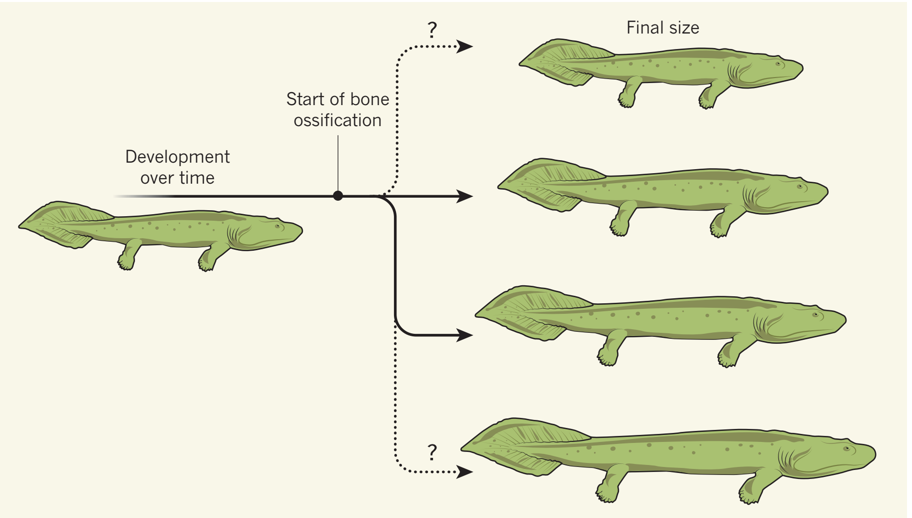

Figure 1 | Possible developmental pathways in the tetrapod *Acanthostega*. Sanchez *et al.*[4] analysed the internal microstructure of fossil forelimb bones of juvenile *Acanthostega*. The authors found that ossification began at a late stage, after the animals had grown to nearly full size, and that there were at least two size classes (solid arrows). The two classes could represent differences in body size for male and female forms, or developmental plasticity in response to intrinsic or environmental factors. Further size classes might have existed (dotted arrows), which could potentially be revealed by larger sample sizes.