GEODYNAMICS

The ups and downs of sediments

Neither recycled oceanic crust nor sediments alone can explain the composition of ocean-island basalts, but how about a mixture of the two? Recent modelling using the isotopes of hafnium and neodymium appears to support this contention.

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For us, recycling involves great effort — sorting empty bottles, collecting old newspapers and taking the broken fridge to the recycling site. The Earth, however, can recycle its waste naturally. The Earth's scum consists of ocean sediments and the rigid layer beneath composed of oceanic crust and the uppermost oceanic mantle. The movement of the tectonic plates ensures that this scum is efficiently disposed off at subduction zones where one plate dives beneath another, back into the deeper parts of the mantle. Within the mantle, these materials then get refashioned into several possible products: dead residues at the core–mantle boundary, enriched regions, or hot low-density plumes that rise through the mantle to melt and create new crust at ocean islands such as Hawaii or Samoa. The isotopic compositions of lavas that ooze from such ocean islands have long been thought to provide evidence of the recycling of subducted material into upwelling plumes[1]. On page 64 of this issue, Chauvel and co-authors[2] reproduce the hafnium and neodymium isotopic compositions of ocean-island basalts by simulating the mixing of ancient oceanic crust, as well as sediments, with the ambient mantle. Their results suggest that both subducted oceanic crust and sediments are important recycled components in the sources of ocean-island lavas.

In most of the Earth's rocks, Hf and Nd isotopes co-vary in a predictable way: the $^{143}Nd/^{144}Nd$ ratios of mantle-derived magmas and continental rocks, plotted against the ratios of $^{176}Hf/^{177}Hf$, fall on a straight line, forming the so-called 'terrestrial array'[3]. However, marine sediments are exceptional in this respect, as they have higher Hf ratios than other rocks at a given Nd ratio, the cause of which has been debated[4,5]. Because of this, if only marine sediments were recycled into the mantle, the mantle Nd and Hf isotopic compositions would deviate from the terrestrial array. This would give a different signature to that typically found for ocean-island lavas. However, oceanic crust does not fit the bill as the source for ocean-island basalts either. Because of the way elements redistribute in the mantle during melting, the material that forms oceanic crust would evolve to give ocean- island basalts with Hf isotopic ratios that are relatively low at a given Nd ratio — that is, the plot would lie below the terrestrial array. Such arguments have been used as evidence against the recycling of ancient oceanic crust or sediment into the source of ocean-island volcanoes[7].

Chauvel and co-authors propose a simple solution to this problem. If neither subducted oceanic crust nor marine sediment alone will generate compositions that plot on the terrestrial array as required, mixtures of the two perhaps would. To test this idea, they simulate the composition of subducted crust as a random mixture of oceanic basalt and sediment in different proportions and from different times in Earth's history. The result is a band of compositions that mimics the terrestrial array, implying that both the oceanic crust and the pile of sediments that accumulates on top of it are subducted into the mantle. There, they remain together, but distinct, for billions of years. When they melt along with the surrounding mantle, they give rise to ocean-island lavas with the Nd and Hf isotopic composition required to explain the terrestrial array.

Models simulating the physical aspects of this process, although providing some support for the hypothesis, also pose some difficulties. Such models predict relatively high temperatures at the surface of subducting slabs, which may cause sediments to rise up to shallower levels before the slab sinks deep into the mantle[8]. It is not clear, therefore, whether significant amounts of sediment can make their

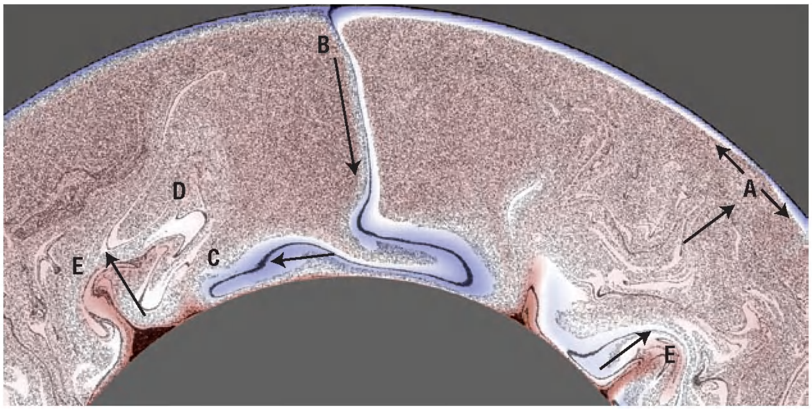

Figure 1 Oceanic crust (black line) collects sediment as it travels from the mid-oceanic ridge (**A**). Upon subduction (**B**), the crust is recycled (**C**) and remixed into the mantle (**D**), and can be brought up passively at mid-oceanic ridges or through plumes (**E**) at ocean island hotspots. Chauvel and co-authors[2] provide quantitative constraints on the relative amounts of sediment, oceanic crust and upper mantle that need to be mixed to explain the Hf–Nd terrestrial array. Image provided by J. P. Brandenburg and based on work in ref. 11.

way into the deeper parts of the mantle. However, if they do manage to reach the deep mantle, the models predict that they will be able to mature there and be mixed and melted to form ocean-island magmas in the fashion suggested by Chauvel and co-authors (Fig. 1).

The Nd–Hf modelling exercise conducted by Chauvel and co-authors is elegant in its simplicity, but several geochemical aspects remain to be tested. Marine sediments vary enormously in their elemental and isotopic composition from place to place[9]. Chauvel and co-authors chose only a single sedimentary composition. Whether this composition is indeed representative of the global average will have to await a survey of the Nd and Hf isotopic compositions of marine sediments subducting at oceanic trenches worldwide. In the modelling by Chauvel and co-authors, time is considered a prime determinant for generating isotopic heterogeneities in the mantle[2]. However, it could very well be that local compositional variations are more important. In addition, other studies have invoked chemical processes internal to the mantle and not external sources such as sediments or oceanic crust, to explain mantle heterogeneity[10,11].

Thus, the debate regarding the external versus internal source of mantle heterogeneity and the ultimate fate of subducting slabs continues. It is likely to be resolved by a better quantification of fluxes into the mantle at subduction zones, improved models that consider composition as well as convection, better resolution of seismic images of the mantle, and consideration of the full suite of geochemical tracers relevant to the problem of recycling within the deep Earth.

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PALAEONTOLOGY

Meteoritic spur to life?

From about 470 million years ago, the Middle Ordovician period witnessed a rapid increase in biodiversity. This explosion in numbers of species is almost perfectly contemporaneous with an increased frequency of meteorite impacts.

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The development of life on Earth has been punctuated by dramatic extinction events and by periods of enhanced biodiversification. The Ordovician period (from about 489 to 443 million years ago) witnessed one of the 'Big Five' mass extinctions in Earth history and also one of the most important intervals of biodiversification, with the emergence of relatives of many of today's marine organisms such as clams and snails. This major increase in biodiversity is sometimes termed as the 'Great Ordovician Biodiversification Event'[1–2], and differs from other periods of biodiversification in that it was not directly related to the recovery of life after an extinction event. Ever since the diversity of Ordovician fauna at a generic level has been evaluated in detail[3], various attempts have been made to identify what drove this biodiversification[1,4]. However, a fully satisfactory explanation had not been offered. On page 49 of this issue, Schmitz and co-authors[5] discuss a fascinating new hypothesis, which relates the increase in biodiversity to an increased bombardment of meteorites around 470 million years ago.

Not only did new phyla — major biological categories that contain several classes of animals — emerge during the Ordovician period, but it was also a time of dramatic increase in the number of species of marine organisms that dwell at different depths in the sea (Fig. 1). In investigating the reasons for these changes, biological aspects, in addition to the more commonly evoked external factors, cannot be ignored. Any comprehensive solution for the Ordovician diversification must give a reason for the enhanced and sustained genetic mutations necessary for the dramatic increase in the number of species. These biological processes can be deeply affected by external factors including extraterrestrial events such as gamma-ray bursts and asteroid or meteorite impacts, as well as by regional or global parameters such as physical and chemical changes in the Earth's environments. A recent review[4] of these factors suggests that they all seem to have influenced the Great Ordovician Biodiversity Event to some extent (Fig. 1).

Schmitz and co-authors argue that an extraterrestrial event — the disintegration of a body in the asteroid belt — played an important role in the Great Ordovician Biodiversification Event by causing sustained impacts of fragments from kilometre-sized asteroids to micrometeorites[6] on the Earth's surface. This bombardment is estimated to have lasted for 10–30 million years after the initial break-up of the parent body[7] and the resultant meteorite fragments can be found in the layers of rocks that were deposited at the time.

Schmitz and co-authors sampled and analysed meteoritic fragments that occur in rocks from the Baltic and Scandinavian regions, as well as from China. They also conducted a detailed analysis of fossil brachiopods — ancient clam-like organisms — from the Baltic and Scandinavian region. Their data suggest that the very first impacts during the Middle Ordovician period in Baltoscandia are perfectly contemporaneous with the onset of the second and faster pulse of the diversification of brachiopods documented in this region (see Figs 2–3