

more detailed mathematical model. This will require new techniques to generate molecular input signals—perhaps based on photons rather than chemicals—for tuning gene expression and protein degradation (7, 8). The study by Mettetal *et al.* is part of a large effort to blend the biological and mathematical structure of living systems and understand living systems not as collections of machine parts, but as stable, complex

dynamic organizations (9). Hopefully, 21st-century systems biology will claim victories as striking as those of Maxwell and Hertz.

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GEOCHEMISTRY

The Rise and Fall of a Great Idea

Anders Meibom

On page 453 of this issue, Lugué *et al.* address a key question in geology (1): Can we determine the provenance of hot-spot lavas by geochemical means? The authors show that the chemistry of Earth's mantle is too heterogeneous to allow the detection of chemical or isotopic signatures of the “mantle plumes” widely held to cause hot-spot volcanism (see the figure).

For decades, mantle geochemists have tried to find a clear isotopic or chemical signature of Earth's outer core in oceanic basalts, which are produced along mid-ocean ridges or at isolated, intraplate islands such as the Hawaiian chain. The latter are often assumed to be associated with deep-rooted upwellings called mantle plumes. Detection of a geochemical signature unambiguously linked with the outer core in such an intraplate basalt would make a very strong case for mantle plumes that originate at the core-mantle boundary (~2900 km below the surface). This would, in turn, have important implications for our understanding of large-scale mantle convection, the long-term stability of different mantle regions, and other fundamental aspects of Earth's interior.

The platinum-osmium (Pt-Os) and rhenium-osmium (Re-Os) isotopic systems have played a dominant role in these studies. ¹⁹⁰Pt is a rare platinum isotope that decays to ¹⁸⁶Os with a very long half-life of ~450 billion years. ¹⁸⁷Re is the most abundant rhenium isotope and decays to ¹⁸⁷Os with a half-life of ~42 billion years. Over time, a system with fractionated (that is, changed) Pt/Os and Re/Os elemental ratios will develop ¹⁸⁶Os/¹⁸⁸Os and ¹⁸⁷Os/¹⁸⁸Os ratios that are different from those in a system in which these elements were not fractionated.

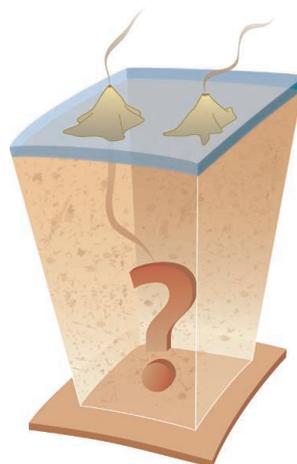
(The stable isotope ¹⁸⁸Os is used for normalization.)

Earth's mantle was strongly depleted in osmium, platinum, and rhenium during core formation, because these elements tend to move into metallic phases. If the osmium concentration is much higher in the liquid outer core than in the surrounding mantle, mixing a little bit of outer-core material back into the mantle at the core-mantle boundary will change the local osmium isotopic composition to resemble that of the outer core. And if the osmium isotopic composition of the outer core is very different from that of the upper mantle, it might be detected in lavas brought to Earth's surface.

This is a great idea. Excitement therefore followed the discovery of enhanced ¹⁸⁶Os/¹⁸⁸Os and ¹⁸⁷Os/¹⁸⁸Os ratios in Hawaiian basalts; a case was made for an outer-core origin of this isotopic signature (2). The logic was that the measured osmium isotopic ratios, particularly ¹⁸⁶Os/¹⁸⁸Os, would not normally exist in the mantle, but that inner-core solidification could produce the required fractionation of osmium, platinum, and rhenium in the remaining outer core. Finally, geologists had what looked like proof of a deep origin of a proposed mantle plume.

But as the assumptions behind the model were examined, problems appeared.

Heterogeneities in Earth's mantle create ambiguity about the origin of hot-spot lavas.



Mantle complexities. Thermally driven upwellings in the mantle—so-called mantle plumes—are often envisioned to originate at the core-mantle boundary, from which they rise to create the hot-spot volcanism seen, for example, in Hawaii. Unambiguous geochemical signatures of the outer core in such hot-spot basalts would prove the existence of deep-rooted mantle plumes, with important implications for large-scale mantle dynamics. But the detection of geochemical signatures uniquely tied to the outer core is severely complicated by a very high degree of upper-mantle heterogeneity, as shown by Lugué *et al.*

First, modeling of osmium, platinum, and rhenium fractionation between the solidifying inner core and the molten outer core is largely unconstrained. We do not know with certainty either the light-element composition of the outer core or the crystal structure of the solid inner core. We know even less about the fractionation behavior of these elements between the inner and outer core.

Second, when the fractionation of osmium, platinum, and rhenium between the inner and outer core was tuned in the model to fit the data from the Hawaiian basalts, the extremely long half-life of ¹⁹⁰Pt required the inner core to have started to crystallize early in Earth's history. This conclusion is in direct conflict with geophysical studies of the evolution of the inner/outer core system (3).

Third, an osmium isotopic signature from the outer core should be accompanied by a distinct signature in the isotopic composition of tungsten. This signature was not found (4).

Finally, osmium isotopic analyses of other mantle-derived materials showed that the upper mantle is very heterogeneous and that the Os isotopic “anomalies” detected in the Hawaiian basalts were probably not that anomalous (5). For example, certain mantle sulfides could have the appropriate Pt/Os and

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Re/Os fractionations to develop the observed ^{186}Os and ^{187}Os enrichments (5, 6), although data supporting such a model were sparse.

Luguet *et al.* now provide the chemical and isotopic data to support this model. Their results radically change the basis on which osmium isotopic compositions from mantle-derived materials are evaluated. There is no longer a need to invoke an outer-core input to explain the osmium isotopic compositions of mantle-derived materials. And there is no geochemical smoking gun for a core-mantle boundary origin of the Hawaiian intraplate volcanism. Instead, there is evidence for a very high degree of geochemical heterogeneity in the upper mantle. This is not only true for the osmium isotopic systems; it seems to

be generally true and has important consequences for explaining the origin of isotopic “anomalies” in mantle-derived materials.

Geochemical heterogeneity is introduced into the mantle, for example, by subduction of sediments, oceanic crust, and lithosphere, and by melt extraction. Other processes can also contribute to the creation of a range of geochemical components in the upper mantle. All these processes redistribute (fractionate) major and trace elements among different minerals, fluids, and melts, which in turn allows different components to evolve along divergent isotopic trajectories.

The concept of isotopic “anomalies” in oceanic basalts thus has to be applied with extreme care. Indeed, with an upper mantle

as heterogeneous as the data by Luguet *et al.* suggest, it is difficult to imagine that isotopic signatures in oceanic basalts can be uniquely tied to the outer core. The debate about the existence and possible origins of deep-rooted mantle plumes will most likely have to be settled with geophysical methods.

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MATERIALS SCIENCE

Structural Nanocomposites

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Materials scientists predict that composites made with nanoscale reinforcing materials such as nanotubes, platelets, and nanofibers will have exceptional mechanical properties. However, the results obtained so far are disappointing, particularly when compared to advanced composites reinforced with high-performance continuous fibers (1–4). The reasons include inadequate dispersion and alignment of the nanoreinforcement, low nanoreinforcement volume fraction, and poor bonding and load transfer at interfaces. Intensive work is under way, but the prospect of bulk structural super-nanocomposites appears more remote now than it did just a few years ago. However, recent work shows that some applications in reinforcement of small structures may have a near-term payoff that can foster longer-term work on nanocomposites.

Most of the work on structural nanocomposites has relied on ultrastrong nanoreinforcement such as single-walled carbon nanotubes (SWCNTs) (1–3). However, the high SWCNT strength has not yet translated into bulk strength, and it is not even clear whether such translation is possible: Any attempt to create strong interfacial bonds will introduce defects into the SWCNTs that reduce their intrinsic strength. Still, multifunctional applications not

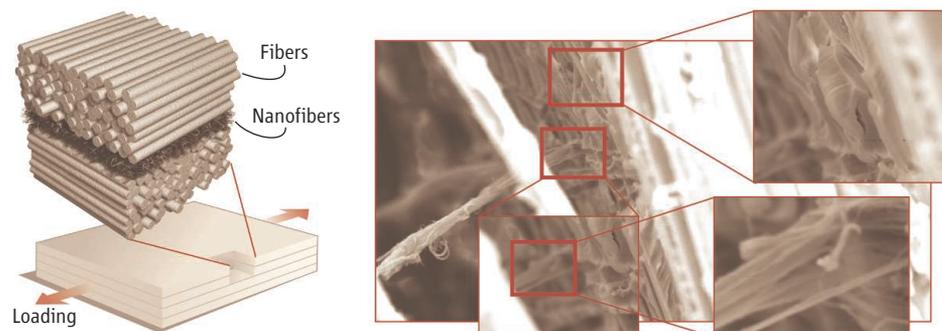
relying solely on the mechanical superproperties will benefit (4, 5). Tailorability and controlled anisotropy are other useful special features of nanocomposites. Multiscale modeling (6) will help us achieve the desired balance between various functions.

One frequently overlooked characteristic of nanoreinforcement is its small size. Various miniature and confined structures can benefit from the improved performance and tailorability of nanocomposites, including ultrathin coatings, membranes, films, and fibers; dental prostheses; structural elements in micromachines and micro- and nanoelectromechanical systems (MEMS/NEMS); thin walls in foams and aerogels; and connections in microcircuits. With the notable exception of nanoreinforced fibers (1, 2), work on the use of nanoreinforcement in microstructures has been slow, but progress is expected to acceler-

ate with the development of more robust nanomanufacturing processes.

Another promising area of research involves solving structural problems that occur in small critical volumes, especially weak spots requiring nanoreinforcement and regions with high localized stress concentrations. Various microdefects and weak inclusions or inhomogeneities represent the former type, whereas sharp structural corners and crack tips are examples of the latter. Cases where both conditions occur simultaneously are the best candidates.

The use of nanocomposites in microscopic structures or critical volumes requires careful multiscale structural design as well as development of techniques to incorporate the nanocomposite in the desired microcomponents. Although the challenges may be great, the resulting applications can be achieved



A pathway to supernanocomposites? (Left) Advanced laminated composite with nanofiber-reinforced interfacial layer. (Right) In situ observation of interlaminar toughening nanomechanisms including Velcro-like crack bridging by nanofibers.

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