GEOPHYSICS

Mapping Earth's deepest secrets

Sequencing seismograms pinpoint new structures near Earth's core-mantle boundary

By **Meghan S. Miller**

Deep within Earth's interior, at ~2900 km beneath the surface, lies the boundary between the solid silicate rock mantle and the liquid iron-nickel alloy core (the core-mantle boundary). Geophysicists have studied the complex thermal and chemical dynamics that take place in this boundary layer. In the early 20th century, Gutenberg investigated the structure of the lowermost region, or base, of the mantle by recording with only a few seismograms from a small number of large-magnitude earthquakes that occurred thousands of kilometers away (*1*). The structure of the rocks just above the core-mantle boundary—designated as D′′ by Jeffreys in 1939 (*2*)—forms a distinct layer with surprising complexity. Now, on page 1223 of this issue, Kim *et al.* (*3*) describe new structural heterogeneities in the lowermost mantle with the use of a learning algorithm that does not require any a priori knowledge of Earth.

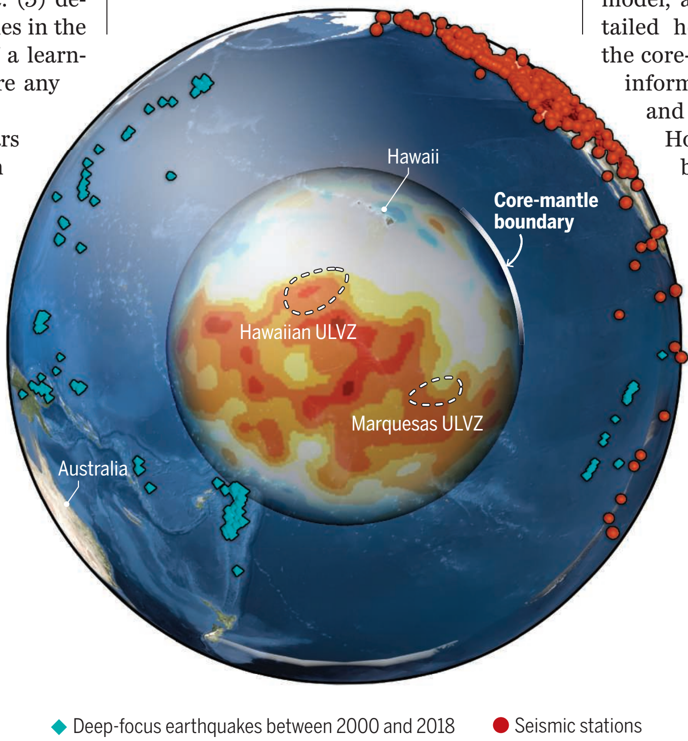
Research over the past ~100 years has yielded major improvements in scientists' understanding of the lowermost mantle. However, the velocity discontinuities (which represent the boundaries between layers within the deep Earth) detected by the pioneers in seismology with just a small number of measurements remain as fundamental constraints of Earth's structure.

Thanks to community experiments such as EarthScope (*4*), the relatively disparate and important observations of the lowermost mantle have increased in number and location with the exponential growth in seismic data collected over the past couple of decades. Seismologists have used seismograms of earthquakes recorded by arrays of distant seismometers to image the deep-mantle structures (*5*). The development of methods, such as those used by Kim *et al.*, to process and analyze increasingly large datasets are crucial to improving geophysicists' knowledge of Earth's structure, which is central to understanding the evolution of Earth.

Global tomographic models at lower mantle depths, such as S40RTS (see the figure) (*6*), were generated from low-resolution (hundred- to thousand-kilometer-scale) images of Earth's structure; such models were hampered by the use of only long-wavelength seismic waves and the type of imaging method. Despite the limitations, these global models illustrate the remarkable complexity of the lowermost mantle, which suggests that this region is one of Earth's most important thermal and structural zones. This part of Earth's interior includes large low-shear-velocity provinces (LLSVPs) and ultralow-velocity zones (ULVZs), which have been linked to hotspot volcanoes and large igneous provinces at Earth's surface (*7*, *8*). The extent and edges of structures that cluster primarily at the edges of LLSVPs [such as the African LLSVP (*9*), the Pacific LLSVP (*10*), and in particular the small-scale ULVZs (*5*, *11*)] traditionally have been mapped by analyzing individual seismic waveforms that sample the deepest mantle.

Only certain seismic phases are sensitive to the LLSVP and ULVZ structures; these include seismic waves that are diffracted off the core-mantle boundary, such as S_{diff} (*6*) and P_{diff} (*12*, *13*), or are reflected at the core-mantle boundary, such as *ScS* or *ScP* (*13*). The waveform distortion of these seismic phases, paired with arrival-time anomalies relative to a preexisting model, allows for inference about the detailed heterogeneities of the rocks near the core-mantle boundary and provide key information regarding the composition and dynamics of the lower mantle. However, after selecting data on the basis of signal-to-noise ratios and sparse earthquake and seismometer (source-receiver) geometries, the seismic waveforms often are analyzed manually and then compared with either one-dimensional (1D) models or 3D models (from tomographic imaging) of Earth's structure. Although there are millions of earthquake records available from seismic networks across the globe, it remains a challenge to analyze and quantitatively assess individual seismic waveform data and extract the desired information. The ability to detect and analyze subtle changes in waveforms is important for providing constraints on the physical parameters of deep Earth.

To this end, Kim *et al.* used a manifold algorithm called "the Sequencer" to investigate a relatively large S_{diff} waveform dataset; the Sequencer enabled a data-driven analysis of the deep mantle without any expectations or prior knowledge



Shaking things up at the center of Earth

Seismic-wave scattering can pinpoint structures beneath Earth's surface, as shown in this tomographic model of Earth and its lower-mantle depths near the core-mantle boundary (center circle). The red-orange region indicates the Pacific large low-shear-velocity province (LLSVP). Green symbols indicate deep-focus (>150 km depth) earthquakes that occurred between 2000 and 2018 and were recorded at distant seismometers (red symbols). The seismograms were analyzed by Kim *et al*. ULVZ, ultralow velocity zone.

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about its structure. This unsupervised, graph-based algorithm orders the waveforms to minimize dissimilarities and can reveal trends without an Earth model. The analysis by Kim *et al.* detected subtle changes in seismic waveforms from earthquakes that occurred in Asia and Oceania and were recorded in the Americas and mapped their origins across a large geographic region beneath the Pacific Ocean.

The new study also identified more broadly distributed ULVZs at the base of the mantle north of Hawaii and a previously undetected anomaly in the deepest mantle beneath the south-central Pacific. This type of analysis could be applied to various seismic phases such as *ScS*, *ScP*, and P_{diff} and a range of others that are of higher frequency, which would provide a new, higher-resolution, and more comprehensive mapping of the structural heterogeneity of deep Earth. Knowledge of these physical properties and of inferred chemical and thermal structures is essential to determining whether partial melt of the rocks exists at the core-mantle boundary, whether distinct materials accumulate or stabilize in particular regions, whether some volcanoes have origins in deep Earth, and, last, what the compositional variations are in the lowermost mantle. ■

> **"... a manifold algorithm... enabled a data-driven analysis of the deep mantle without any expectations or prior knowledge about its structure."**

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ECOLOGY

The global odyssey of plastic pollution

Thinking big about small particles reveals new features of the microplastic cycle

By **Chelsea M. Rochman**[1] *and* **Timothy Hoellein**[2]

Scientists who once studied microplastics (plastic debris <5 mm in size) as ocean pollutants have now detected them in soils, biota, and Earth's atmosphere. To decipher the global fate of microplastics, scientists have begun to ask questions about the "microplastic cycle," which is akin to global biogeochemical cycles (nitrogen, carbon, and water). For example, what are the sources of microplastics, and how do they transform as they move from one pool (e.g., a beach, inside an organism, or a river bed) to another? And what processes ("fluxes") transfer microplastics between pools? On page 1257 of this issue, Brahney *et al.* (*1*) report high-resolution spatial and temporal data that provide evidence of both global and regional microplastic transport, thus increasing our understanding of the microplastic cycle.

Nearly a decade ago, scientists began studying marine microplastics in surface currents of the ocean as the key mechanism for global transport. As datasets grew, their understanding of long-range transport within and between oceans expanded to include mechanisms such as deep-sea circulation (*2*), biological transport (*3*, *4*), and drifting sea ice (*5*). In parallel, emerging work uncovered pools of microplastics in other Earth compartments, including freshwater and terrestrial systems (*6*), and the atmosphere (*7*). To fully understand the microplastic cycle, researchers must piece together the fluxes that connect the transport and transformation of microplastics as they move between planetary compartments.

Atmospheric transport of microplastics in airborne dust, which settles to the ground (deposition) during dry and wet periods and in both urban and remote locations, was initially overlooked. Scientists have understood the global transport of dust for decades, but until recently, dust was not known to carry substantial amounts of microplastics. Seminal work on transport of microplastics in the atmosphere demonstrated their presence in wet (e.g., rain, snow) and dry deposition in Paris, France (*8*), providing proof that microplastics are a component of dust and that atmospheric deposition is a mechanism of transport. Long-range atmospheric transport, away from urban centers, was first demonstrated in 2019, when microplastics were unearthed from a remote mountain catchment (*7*) and in Arctic snow (*9*). These studies prove that microplastics are transported atmospherically to both regional and faraway places.

Brahney *et al.* studied both global and regional transport of microplastics by comparing the size and shape of particles deposited in dry and wet weather (see the figure). The new work elucidates patterns of deposition and processes of atmospheric transport, and predicts that atmospheric transport is an important source of microplastics in remote locations. For example, the authors estimate that more than 122 tons of microplastics are deposited annually to U.S. protected lands of the western United States.

By incorporating human population metrics, local weather patterns, and climate models, Brahney *et al.* found that larger microplastics were deposited during wet events and likely originated from nearby urban centers during regional storms. In contrast, smaller microplastics deposited during dry weather were more likely to have been transported long distances and made up the majority of the microplastic mass.

A key insight from the new work is that fundamental tools for studying global dust transport can be applied to microplastics. Like dust, most particles measured were within the size range typical of global transport (<25 μm). However, microplastics are less dense than soil and therefore might travel longer distances than natural dust particles. Future research should test hypotheses about the distances that microplastics can travel atmospherically and the processes that entrain microplastics in the air, such as sea spray and dust storms. The new study also invites questions about latitudinal gradients. Global atmospheric circulation is affected, in part, by air rising at 0° and 60° latitude and

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