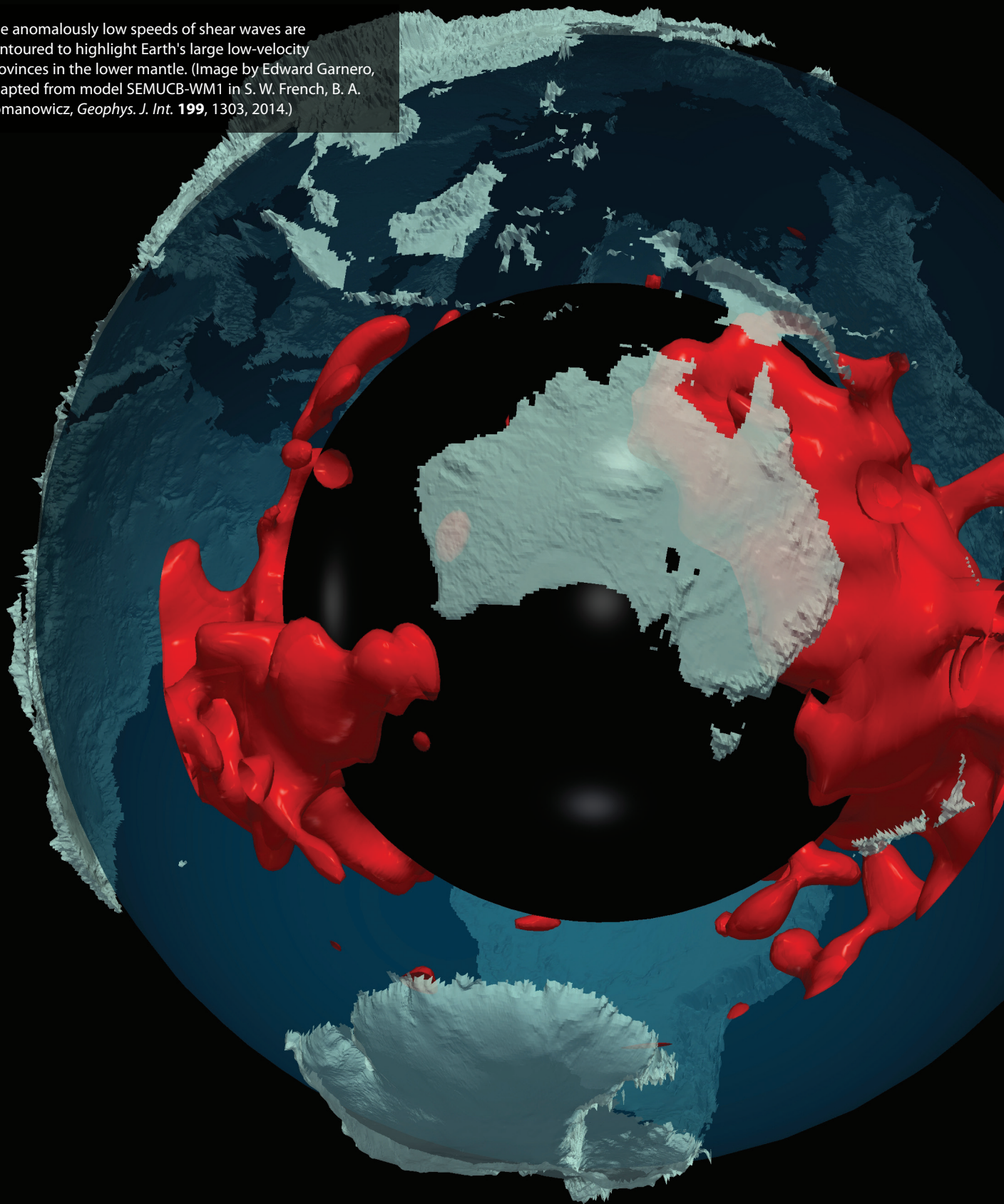


The anomalously low speeds of shear waves are contoured to highlight Earth's large low-velocity provinces in the lower mantle. (Image by Edward Garnero, adapted from model SEMUCB-WM1 in S. W. French, B. A. Romanowicz, *Geophys. J. Int.* **199**, 1303, 2014.)



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The mysterious, massive structures in Earth's deep mantle

Edward Garnero and Claire Richardson

Seismic waves traversing the interior of the planet reveal continent-sized regions with distinct physical properties. Researchers are investigating what they are, how they got there, and what their role is in Earth's dynamic convecting interior.

Roughly 3000 km below us, almost halfway to the center of Earth, lies the boundary between the solid rock mantle and the predominantly liquid-iron outer core. Grade-school textbooks typically depict Earth's interior as basic, brightly colored concentric shells of the crust, mantle, outer core, and inner core. But recent research dramatically alters that simplistic view to include two enormous anomalous structures sitting at the base of the mantle, on top of the core–mantle boundary. Positioned on nearly opposite sides of the globe, one anomaly is underneath the Pacific Ocean, and the other sits beneath western Africa and parts of the Atlantic Ocean.

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The two structures are the size of large continents and extend in some places more than 1000 km vertically into the mantle. Those massive features, called large low-velocity provinces (LLVPs), are characterized by significant reductions in seismic wave velocities for both shear and compressional waves (commonly known as *S* and *P* waves, respectively). The speed at which seismic waves travel depends on the composition and temperature of the media that they travel through. For example, heating a rock causes seismic waves to slow down, while cooling it causes them to speed up. Thus, maps of variations in seismic wave speeds, like the two shown in figure 1, can be used to infer properties of Earth's interior.

Seismic images of Earth's deep interior have been foundational in progressively revealing its character. The nature of the interior continues to be illuminated through the detailed study of vibrations traveling through the planet. Insights gleaned from seismic studies include better understanding of phenomena such as internal convection, mantle plumes, the

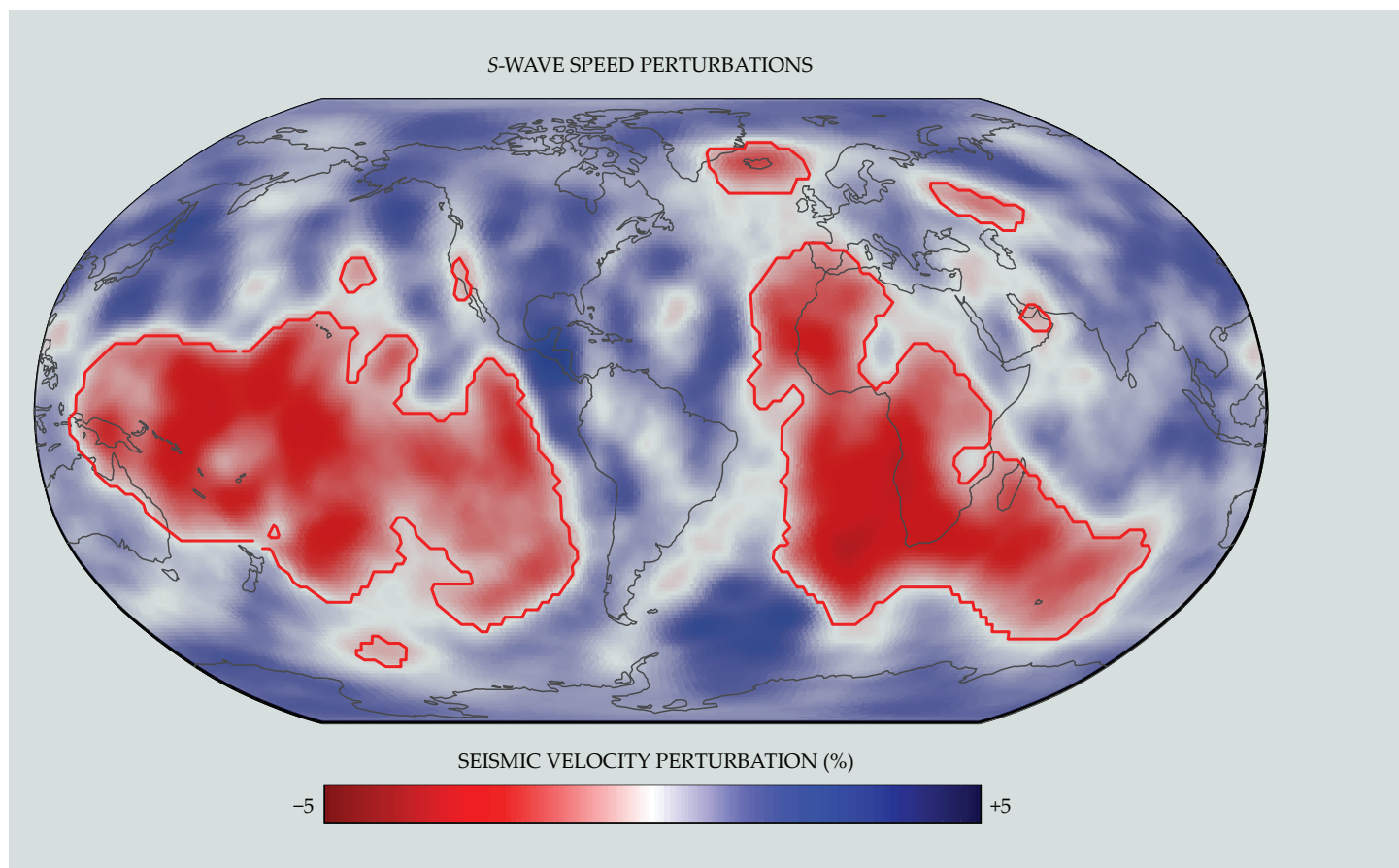
fate of tectonic plates descending into the lower mantle, planetary geochemical cycles, heat flowing from the core to the mantle and giving rise to the magnetic field, Earth's evolution, and even supercontinent cycles.

Using earthquake waves that travel deep into Earth's mantle, researchers have observed the sides of LLVPs to be seismically sharp—that is, the velocity reduction from the surrounding mantle rock to an LLVP occurs over a relatively short lateral distance. That appears incompatible with a solely thermal explanation for LLVPs, which would predict a more gradual transition of wave speeds from the surrounding lower mantle to LLVP regions. Most current explanations for the origin of LLVPs, therefore, center on their material being compositionally different from the surrounding lower mantle rock's, with the LLVP material producing much lower wave speeds.

Slow motion discovery

The discovery of LLVPs was not sudden but rather involved several decades of studies by researchers worldwide. The ear-

FIGURE 1. SEISMIC WAVE SPEED PERTURBATIONS can be used to discern changes in temperature and composition in Earth's interior. Seismic tomography uses the waves from earthquakes around the globe to produce 3D maps of how the speeds of shear (*S*) and compressional (*P*) waves differ from the predictions of 1D reference velocity models, in which values change only with depth. Shown here are *S*-wave and *P*-wave perturbation maps for the lowermost 100 km of the mantle. Two large low-velocity provinces, outlined in red, cover around 30% of Earth's core–mantle boundary surface area. (Adapted from ref. 16.)



liest work entailed a method called seismic tomography, which, like medical tomography, utilizes up to millions of waves traversing the medium of interest—Earth’s mantle—to image the interior. Tomography revealed evidence for velocity reductions over very large scales (for example, smoothly varying speeds over about 10 000 km), which led to the idea that rocks in those regions are warmer.¹ Researchers continue to use tomographic studies to refine details of deep-mantle heterogeneity.

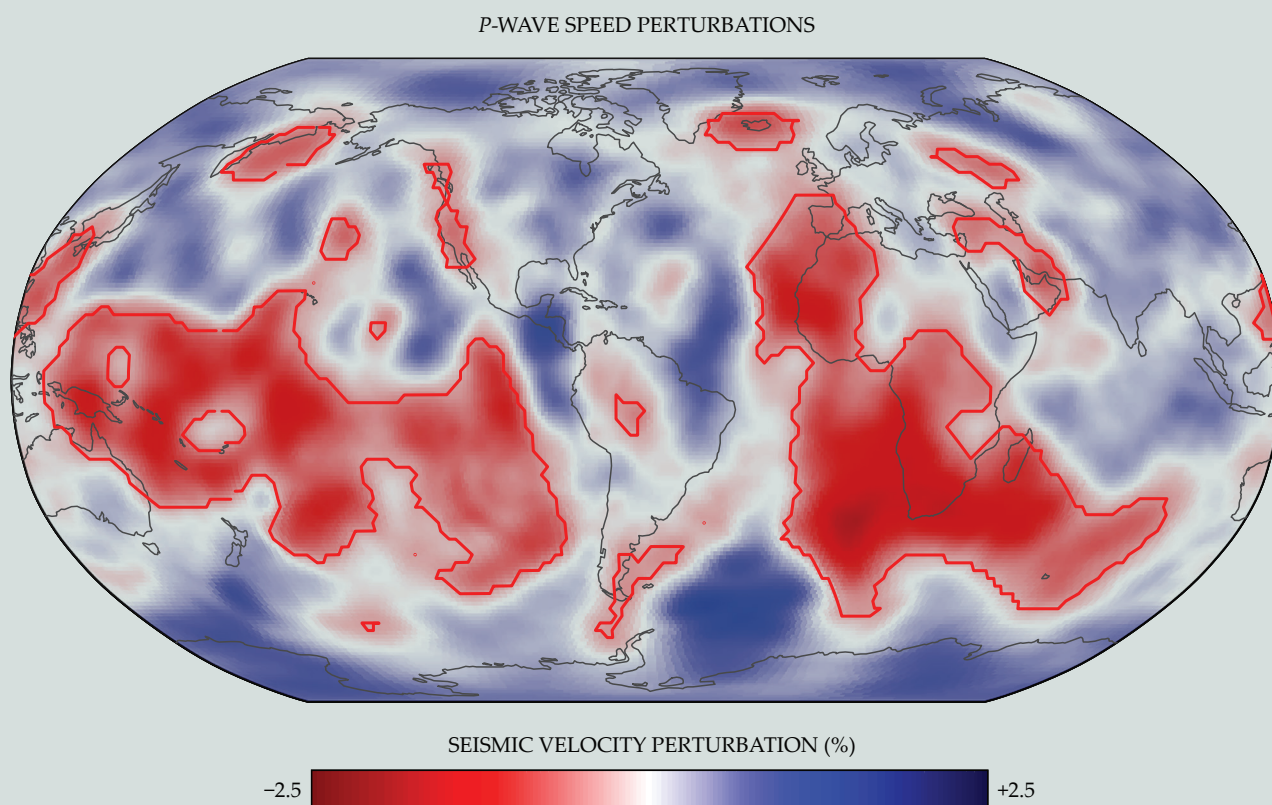
Just over 20 years ago, seismologists studying the pulses of energy that pass through the deepest mantle found an additional “bump” in the waveforms, which was produced by the movement of waves on both sides of the sharp LLVP margins.² The bump provided the first hint that the LLVPs were compositionally different from the surrounding mantle.³ The finding also indicates that LLVPs must be made of material that is intrinsically denser than the typical mantle rock they displace. Without that higher density, they’d be swept away and upward by mantle convection currents.

Density depends on both temperature and composition. Some denser rocks, such as those containing elevated iron content, can have reduced seismic wave speeds because wave speed is affected by both the density and strength of a material. From their long-lived, stable position above the hot core,

LLVPs have elevated temperatures that should make them less dense. But the density increase caused by the LLVPs’ composition may be greater than the density reduction caused by their elevated temperature. LLVP density remains an active area of research.⁴

Akin to the way that images of distant galaxies have come into focus because of the advancement from Earth-based telescopes to the *Hubble* and *James Webb* space telescopes, refinement of seismic imaging techniques has brought details of Earth’s interior into clearer view. That improvement has been greatly assisted by the continually growing number of seismic sensors around the planet. And with seismic imaging, much like ultrasound and MRI techniques for imaging the human body, the greater the density of crisscrossing energy recorded by well-distributed sensors, the better the imaging abilities. Refinement of computational tools has also contributed to advances in seismic imaging.

Current seismic images reveal that just as large continents have specific shapes and varying details to their coastlines, LLVPs exhibit intricate and uneven 3D shapes that significantly depart from the smoothly varying structures presented in early renderings. For example, the African LLVP extends farther up into the mantle than the Pacific



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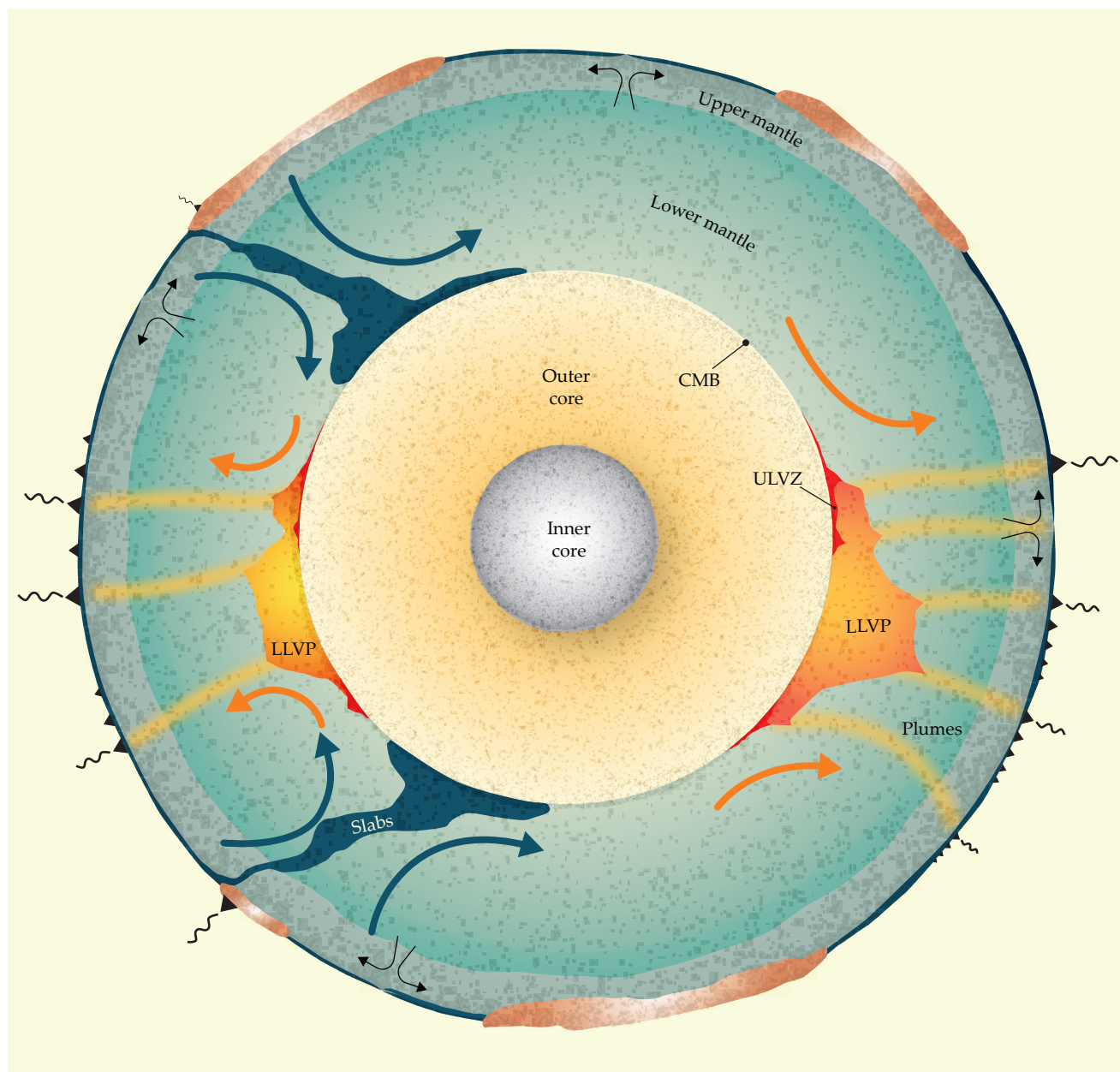


FIGURE 2. TWO CONTINENT-SIZED LARGE LOW-VELOCITY PROVINCES (LLVPs) sit in the lower mantle of Earth's dynamic interior. The LLVP structures extend roughly 1200 km above the core–mantle boundary (CMB) in places and are likely compositionally distinct from the surrounding mantle rock (green). The convection forces that shape the anomalies are nonuniform and related to mantle currents induced from subducting slabs (blue structures in the mantle), which were once tectonic plates in oceanic regions (blue outer shell). Mantle plumes (yellow) have been mapped to originate near LLVP margins. Plumes give rise to hot-spot volcanism (black triangles at the surface). Thin anomalous structures that may be partially molten, called ultralow-velocity zones (ULVZs, dark red), are also found near LLVPs.

LLVP.⁵ That raises the possibility of differing density structures—and possibly different chemistries—between the two anomalies.

The strength of convective flow around the LLVPs could also differ. Deep-mantle convective flow strength is primarily controlled by subduction, the process of tectonic plates falling into the interior when they become cold and dense

enough. Subduction-related downwelling flow varies according to tectonic plate speeds, locations, and densities as the plates fall into the mantle.

LLVP shape is closely linked to the surrounding dynamic mantle. Increasingly finer-scale features of LLVPs are visible in seismic images made with modern modeling capabilities. But imaging limitations remain because the uneven

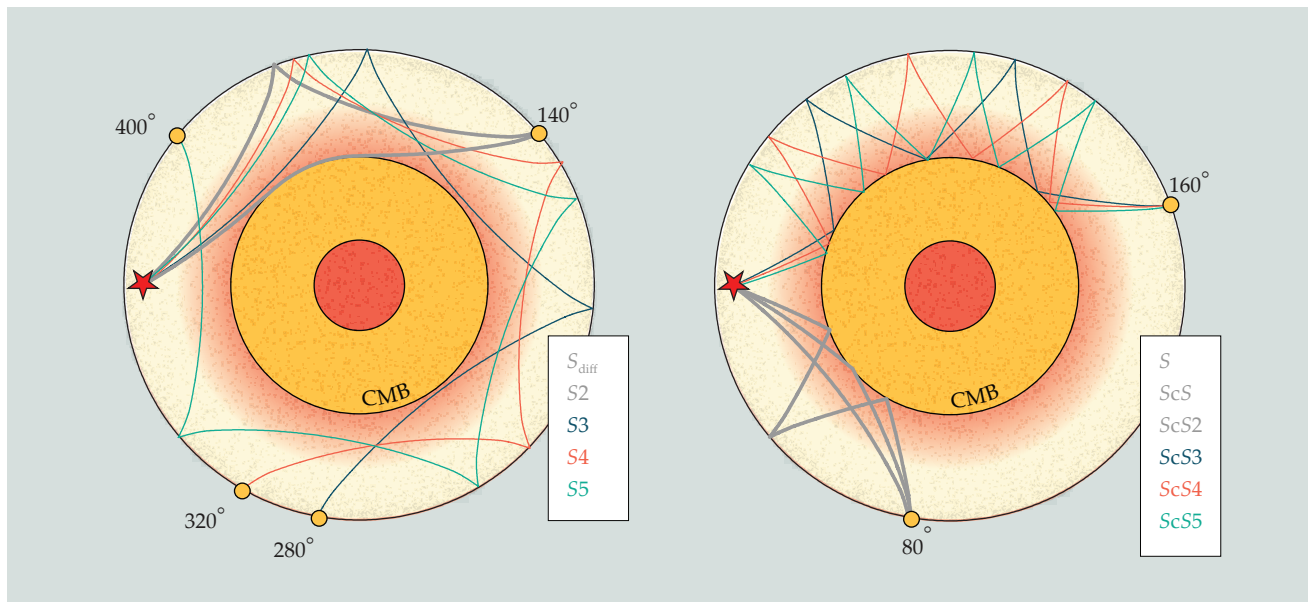


FIGURE 3. ECHOES OF SEISMIC WAVES produced by refraction and reflection from the underside of Earth's surface (**left**) and off the core–mantle boundary (CMB; **right**) add additional and redundant sampling of the lower half of the mantle (light red shading), where large low-velocity provinces reside. Seismic waves, depicted by their ray paths, are shown for *S* waves between an earthquake (red star) and receiver locations (yellow circles). Ray paths (gray) commonly analyzed by seismologists include direct *S* waves (*S*), diffracted *S* waves (*S_{diff}*), *S* waves that bounce once between earthquake and receiver (*S2*), and *S* waves that bounce off the CMB once and twice (*ScS*, *ScS2*). Waves having additional reflections are less commonly used but are present in the data. Those include *S* waves with multiple reflections off the surface (*S3*, *S4*, *S5*) and off the CMB (*ScS3*, *ScS4*, *ScS5*). Measuring all available *S* and *P* waves will improve tomographic images of the deep Earth.

global distributions of seismometers and of earthquakes create uneven sampling of the interior.

Learning from LLVPs

As seismic imaging of LLVPs has improved, the importance of LLVPs for understanding the dynamic and mineralogical properties of Earth, throughout its 4.5-billion-year history, has become increasingly apparent. The low-resolution, smooth structures in the earliest images of LLVPs were thought to be solely the result of temperature variations caused by large-scale mantle convection currents. Convection in the mantle is like convection in a pot of boiling water: Cold material sinks, and hot material rises. The mantle, however, is predominantly solid rock, and thus convection is extremely slow, occurring on time scales of millions of years.

As tectonic plates, often referred to simply as slabs, sink from Earth's surface into the interior at subduction zones, the surrounding mantle is pulled viscously downward with them, as illustrated in figure 2. Once slabs reach the base of the mantle, they convect laterally along the core–mantle boundary toward warmer upwelling regions. Those warmer zones are thought to harbor the roots of hot mantle plumes that rise through the entire mantle and lead to hot-spot volcanism that occurs above LLVPs, such as in Hawaii. The reduced velocities found in tomographic images in the 1980s

and 1990s supported that model of hot, plume-generating LLVPs.

When sharper sides of LLVPs were detected starting in the 2000s, however, the dominant hypothesis about their material changed from its being purely a result of thermal differences to being both thermally and compositionally distinct from the surrounding mantle. That hypothesis, which carries significant consequences for unraveling the dynamic behavior and composition of the mantle, remains the prevailing view.³

If any compositionally distinct material exists at the base of the mantle, it, too, is subject to the forces of mantle convection and is swept toward regions of convective upwelling currents. If the material is denser than that of the surrounding mantle, it will stagnate beneath upwellings, resulting in piles of material. Thermochemical simulations of mantle convection over the past 120 million years agree with findings from seismology about the locations of those chemically distinct piles.⁶ Long-lived, chemically distinct LLVPs may therefore contain chemical signatures from earlier in Earth's history.

The piles can be slowly eroded as convection entrains small amounts of their material in mantle plumes. The plumes deliver some of the material to the surface, where it shows up in hot-spot volcano eruptions as trace-element isotopic anomalies.⁷ In fact, the locations of hot-spot volcanoes, as well as the original location of Earth's largest volcanic eruptions responsible for massive accumulations of igneous

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rocks, predominantly overlay LLVP margins. Those locations are consistent with geodynamical convection predictions of mantle plumes that rise off the LLVP edges.⁸ Compositionally distinct LLVPs will also modify patterns of heat flow from the core into the mantle, which affect the convective currents in the liquid outer core that generate Earth's magnetic field.⁹

Although many questions about LLVPs have been answered by modern seismic imaging, many more are arising with new images. For example, it's possible that broad, large upwellings extend from the top of LLVPs.¹⁰ The upwellings have been referred to as superplumes in past literature; tomography, however, presents just a snapshot in time of anomalous seismic wave speed patterns, and convection experiments are required to assess the likelihood that material is ascending, descending, or neutrally buoyant.

Another interesting possibility relates to supercontinent cycles, in which supercontinents, such as Pangaea, repeatedly form and break up over hundreds of millions of years. Mantle convection models have shown that during such cycles, compositionally distinct LLVPs can merge on the opposite side of the globe from the supercontinent and then return to two antipodal LLVP piles when supercontinent breakup occurs.¹¹

Do upward advecting pieces of LLVPs eventually become the large accumulations of igneous rocks seen at Earth's surface? Are the two LLVPs composed of the same material? Do LLVPs migrate along the core–mantle boundary over time? Questions like these are topics of ongoing research.

Terrestrial or extraterrestrial?

If a convecting system has large enough density perturbations from composition or temperature effects, anomalous structures can reside at either the top or bottom—buoyant material at the surface, denser material at the base. Otherwise, they will mix into the background material over time. Hence, hypotheses for the origin of compositionally distinct LLVPs involve either their slow growth over time from the accumulation of dense material or their quick growth when Earth formed or shortly thereafter.

The slow crystallization of Earth's mantle from an early magma ocean may have facilitated the creation of LLVPs: Denser minerals would have crystallized first and then sunk to the mantle's base, where they may have experienced subsequent chemical alteration.¹²

Several possibilities for slow-growing, dense LLVPs have been raised over the years. One is the accumulation of relatively dense, iron-rich, subducted former oceanic crust over geologic time scales. The outermost core can also contribute to anomalous material in the deepest mantle through processes that involve chemical exchange across the core–mantle boundary. For example, a recent study suggests that hydrogen stored in former oceanic crust subducted to the core–mantle boundary can be exchanged for carbon in the core.¹³ That process might occur over much smaller volumes than LLVPs, but it could explain the origin of some small-scale features known

as ultralow velocity zones, also found above the core–mantle boundary, that have extreme seismic velocity reductions.

Early in Earth's history, shortly after the solar system formed, a Mars-sized planet named Theia is hypothesized to have collided with proto-Earth to form the Moon. The Moon thus likely began its existence with contributions from both Earth and Theia. Because the Moon's volume is a fraction of that hypothesized for the much larger Theia, the question, Where did the rest of Theia go? provides an interesting possibility for the origin of Earth's LLVPs. Qian Yuan and colleagues present a case for Earth's massive lower-mantle anomalies being dense Theia remnants¹⁴—in other words, extraterrestrial. If planetary collisions were common in the early solar system, it's interesting to consider whether remnants of impactor bodies reside in other planetary bodies as well.

Improving our seismoscope

Although we now know the large-scale shapes of LLVPs, sharpening the focus on the finer-scale details has its challenges. We are imaging massive structures up to 3000 km below Earth's surface with earthquake waves that imperfectly sample the interior. Seismic tomography uses those waves to produce images of heterogeneities in wave speed throughout Earth's mantle. Medical tomography, such as CAT scans, uses the same method but differs in a couple of key aspects. First, the locations of the energy source and its recordings can be controlled. Second, the energy can be administered as redundantly as needed.

In deep-Earth imaging, the earthquakes that act as the energy source are far from being uniformly distributed. Furthermore, seismic sensors are predominantly on land, and they're irregularly spaced, with some continents only sparsely instrumented. Thus, the efficacy of seismic imaging is geographically variable. Still, LLVP models from different research groups agree quite well, especially for features at longer length scales (1000 km or more).¹⁵ Smaller-scale features (less than 1000 km), including LLVP attributes and ultralow velocity zones, differ among models, which may result from the amounts and types of data used and the imaging methodology employed.

Continuing to increase seismic sensing across the planet, especially in the ocean and on poorly instrumented continents, will bring better agreement to finer-scale details in tomographic imaging. In the meantime, incorporating less commonly used seismic waves that bounce multiple times through the interior, as shown in figure 3, can further improve coverage, without the time, labor, and cost required for deploying more sensors.

Earthquakes are the primary source of energy used in seismic imaging of the mantle. Roughly 140–150 earthquakes of magnitude 6 or larger happen every year, each of which can be used in deep-mantle seismic imaging studies. Data from thousands of seismic sensors are freely available; every earthquake has up to tens of unique seismic waves that can be measured: Waves can reflect multiple times from the underside of

Earth's surface and off the core–mantle boundary (see figure 3). Many of those waves are not routinely used in tomography—but they can be.

The amount of information available for Earth imaging continues to grow, with several millions of measurements already made. The densification of interior sampling will result in continued improvement in LLVP resolution. But interpreting a larger amount of data is not without challenges. Not too long ago, seismologists personally viewed and hand-measured all their data. Now, far too many measurements are recorded from millions of seismic waves—with more earthquakes and recordings happening continually—than humans can visually inspect.

Processing that much data is possible only with software, and so scientists are turning toward automation, machine learning, and AI to carry out analyses. Although that dramatically increases the number of usable measurements, it also introduces potential for error. Training algorithms to know the difference between high-quality and low-quality data is an active area of research.

Seismic imaging provides a present-day snapshot of Earth's interior. To put that in a context of the time evolution of the planet, with meaningful information about Earth chemistry and mineralogy, cross-disciplinary research is necessary. Geodynamicists use dynamical flow simulations

to predict temperature and compositional patterns in Earth's interior. Mineral physicists investigate the mineralogy of the interior and reproduce those chemistries in high-pressure laboratory experiments. Combining those analyses with, for example, knowledge about the chemistry of erupted lavas, the generation and nature of Earth's magnetic field, and tectonic motions at Earth's surface, we continue to learn more about the origin and evolution of Earth's massive deep-mantle LLVPs and how they relate to important surface phenomena.

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