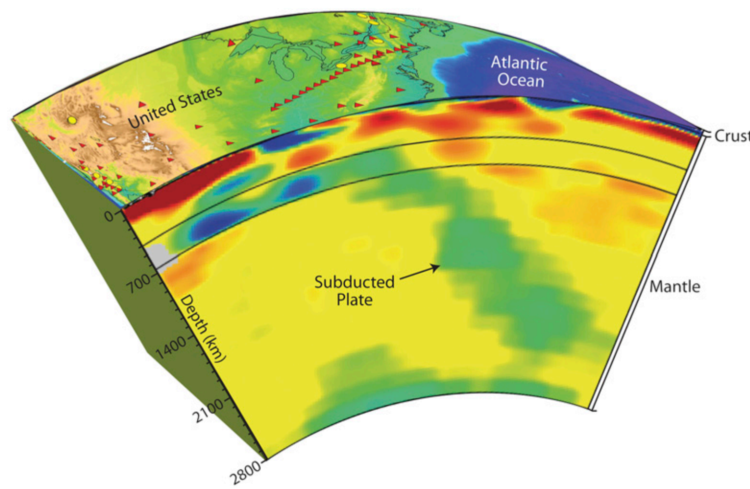
Seismic tomography uses earthquake waves to probe the inner Earth

Sid Perkins, *Science Writer*

Computerized tomography (CT) scans revolutionized medicine by giving doctors and diagnosticians the ability to visualize tissues deep within the body in three dimensions. In recent years, a different sort of imaging technique has done the same for geophysicists. Seismic tomography allows them to detect and depict subterranean features.

The advent of the approach has proven to be a boon for researchers looking to better understand what's going on beneath our feet. Results have offered myriad insights into environmental conditions within the Earth, sometimes hundreds or even thousands of kilometers below the surface. And in some cases, the technique offers evidence that bolsters models of geophysical processes long suspected but previously only theorized, researchers say.

Seismic tomography "lets us image Earth's structures at all sorts of scales," says Jeffrey Freymueller, a geophysicist at Michigan State University in East Lansing and director of the national office of the National Science Foundation's EarthScope. That 15-year program, among other things, operates an array of seismometers—some permanent, some temporary—that has collected data across North America. Among its more impressive finds: the remnants of an ancient tectonic plate sitting deep below North America and a plume of buoyant material fueling a well-known geothermal hot spot.



Data gathered by a network of seismic instruments (red) have enabled researchers to discern a region of relatively cold, stiff rock (shades of green and blue) beneath eastern North America. This is likely to be the remnants of an ancient tectonic plate. Image credit: Suzan van der Lee (Northwestern University, Evanston, IL).

Dissecting the Earth

Tomography, roughly translated from Greek, means "writing by slices." Researchers relish this ability to take digital models of three-dimensional (3D) objects and slice through them to create cross-sections—to virtually dissect them from any angle. Both medical tomography and seismic tomography use large arrays of sensors to collect energy that has traveled through a given body. Medical tomography typically uses differences in the amounts of transmitted energy to create images with blacks, whites, and shades of gray.

But seismic tomography uses differences in the speed of seismic waves as they travel through Earth to construct its 3D model. In general, vibrations travel more slowly through rocks that are hotter or less dense, contain hydrated minerals, or are partially melted. On the other hand, seismic waves travel more quickly through rocks that are colder, denser, and drier. By knowing the precise time at which a distant earthquake occurred, as well as the times at which vibrations from that temblor arrived at each seismometer in a network, researchers can "invert" the data and map out the portions of the planet that those seismic waves had traveled through.

Before seismic tomography came along, geophysicists could only imagine what might be happening deep within Earth. The ability to probe thousands of kilometers underground can help researchers better decipher how those processes are affecting our planet's surface.

"Seismic tomography has revolutionized our understanding of tectonics and allows us to identify connections between the deep mantle and Earth's surface," says Laura Webb, a geologist at the University of Vermont in Burlington.

Long Time Buried

Using EarthScope data, researchers have gained innumerable insights into what lies beneath North America—and the geophysical effects those features have had, and are still having, on the continent. Many

A continent-wide network of seismometers like this one, which was installed in south-central Alaska in 2016, helps researchers probe Earth's inner structure. Image credit: EarthScope National Office, a National Science Foundation funded project/Max Kaufman. EarthScope scientists study the structure and evolution of the North American continent using three primary observatories, the Plate Boundary Observatory, US Array, and the San Andreas Observatory at Depth. For more information, visit www.earthscope.org.

of these result from the subduction of a tectonic plate that began off North America's Pacific coast more than 165 million years ago. Although seismic tomography shows that the western edge of that ancient slab of ocean crust—which geologists have dubbed the Farallon Plate—still lies offshore, the bulk of it lies beneath the western United States. Fluids that were squeezed from the slab as it was shoved eastward beneath the continent rose to hydrate the underside of Earth's crust. Later, the languid motion of the underlying mantle buoyed the crust upward, gradually elevating the Colorado Plateau (1). The results of that process are indeed impressive, Webb notes: That steady boost in the crust, over time, enabled the region's rivers to carve spectacular canyons.

Farther east, remnants of the Farallon Plate sit beneath the Midwest, where they've shed even more water to create a weak zone that stretches from just below the crust there to depths of around 200 kilometers (2), says Webb. That weak spot, not coincidentally, lies right beneath the New Madrid Fault Zone—which spawned some of America's largest earthquakes about two centuries ago. As the ancient slab slowly sinks, mantle flow around it creates a downward suction that stresses and deforms the overlying crust (3). Those stresses, if large enough, can trigger earthquakes. "Seismic tomography has shed new light on how this region can be so seismically active despite being far from tectonic plate boundaries where most large earthquakes occur," Webb notes.

From Titanic to Tiny

But seismic tomography can discern things far smaller than kilometers-thick slabs of subducted material. A slowdown in the seismic waves passing beneath Yellowstone National Park provides evidence for a deep-rooted plume of warm, buoyant material rising to the surface there (4). Geophysicists have long theorized that such plumes fuel volcanic activity at so-called hot spots around the world. Similarly, seismic tomography has offered views into the mid-to-low-level portions of Earth's crust beneath the park. There, a substantial slowing of seismic waves betrays the presence of a 46,000-cubic-kilometer blob of partially melted rock that connects the deep mantle plume to the shallow magma reservoir that's the heat source for the region's famed geysers (5).

On an even smaller scale and using a small network of a few dozen seismometers, researchers mapped out parts of the plumbing system beneath Mount Erebus, a volcano in Antarctica (6). During the 2008–2009 field season, the team set off a dozen small blasts on or near the peak, which was surrounded by a roughly 4-kilometer-by-4-kilometer network of 23 seismic instruments that had been deployed the previous summer. The seismic data from those blasts revealed that a large blob of magma—which in some places slowed down seismic waves by as much as 1 kilometer per second—lies beneath the northwestern slope of the volcano. The tubes that occasionally channel molten rock to the surface during eruptions are too small to be discerned by the analyses, the scientists report, but the volcano's magma chamber, which lies at least 500 meters below the surface, shows up clearly. Long-term studies of active volcanoes could reveal how changes in the size and shape of those peaks' magma reservoirs correlate with eruptions.

One of seismic tomography's most impressive coups, however, may be spotting regions of rock kilometers below Earth's surface where the minerals' atoms may be arranged differently from those in surrounding regions or at different depths (7). Using data gathered by researchers in previous studies, Fan-Chi Lin, a geophysicist at the University of Utah in Salt Lake City, and his colleagues used tomography to image Earth's crust beneath the Yellowstone caldera in Wyoming and the Long Valley caldera in California.

For their study, the researchers added an extra layer to the tomographic analysis: They not only estimated differences in the overall velocities of seismic waves passing through the crust, but they also looked at the differences between the speeds of horizontally polarized seismic waves compared with those that were vertically polarized.

Those findings suggest that the rocks lying beneath the Yellowstone and Long Valley calderas at depths of between 5 and 18 kilometers were likely arranged in a number of horizontal layers. Some of those layers could be only a few meters thick, says Lin, and as much as 6% of the rock within them could be melted. And that slushiness, in turn, could have big implications for how quickly, on geological timescales, those reservoirs of mushy rock could mobilize to generate future eruptions, the researchers say. If geophysicists based their long-term predictions on analyses that didn't include layers of partially molten rock, they could dramatically underestimate the time it could take for that rock to move into a magma reservoir that could someday generate a major eruption.

Just Beneath the Surface

Researchers don't need to use seismic waves from distant earthquakes—or from blasts they triggered themselves—to perform seismic tomography. They can also use the near-continual low-level shimmies that shake the ground and sometimes interfere with measurements of distant quakes. Geophysicists can use this "seismic hum" the same way that photographers use dim light at night: Added up over time, the energy is sufficient to generate an image, explains Keith Koper, another geophysicist at the University of Utah in Salt Lake City. His analyses have shown that the seismic vibrations generated by waves on six lakes in North America and in China—even lakes that cover less than 300 square kilometers—can shake the ground up to 30 kilometers away from those bodies of water (8).

Ocean surf, including the waves pounding the Pacific coastline, also generates seismic hum. Researchers in southern California recently used data recorded in 2015 by 315 seismometers across the region to map out fault zones and other geological features in the area (9). Many of those features—such as the deep structure of the San Andreas, Hayward, Whittier, and other fault zones—were known from previous tomographic studies. But by including new information, such as the size of the seismic waves as well as their arrival times, the new tomographic image has a much better resolution of smaller features that lie within the upper 3 kilometers of the crust. This enhanced mapping of fault zones and sediment depths could improve future analyses of the region's seismic risk, the team suggests.

Following up on earlier field work, Koper and his team deployed a few seismometers on the floor of Yellowstone Lake last summer. Those instruments, as well as others in a shore-based network, will record vibrations generated by the lake's waves as well as those generated by innumerable small quakes in the Yellowstone area. Using that data, Koper and his colleagues will try to map the plumbing system that feeds hydrothermal vents beneath the northern end of Yellowstone Lake.

> **"This data will be mined for a long time to come."**
> **—Jeffrey Freymueller**

"Those vents are, in essence, underwater versions of the geysers seen elsewhere in Yellowstone," Koper notes. Such efforts are just another example of how discerning what's hidden beneath Earth's surface can help researchers better understand the processes unfolding at ground level.

The National Science Foundation's funding for EarthScope has ended, but the program's legacy will last far into the future. About 80 of the nearly 300 seismometers temporarily installed in Alaska over the past few years will be "adopted" by the US Geological Survey or the University of Alaska Fairbanks, says Robert Woodward, director of instrumentation services for Incorporated Research Institutions for Seismology (IRIS), a Washington, DC-based consortium of universities. The remainder will be decommissioned and removed over the next couple of field seasons. IRIS will recalibrate and loan out those instruments to seismologists pursuing short- and long-term projects in the coming years, says Woodward.

In the meantime, says Freymueller, EarthScope data will be archived and maintained so that as new analytical techniques are developed researchers can take fresh looks at old measurements. "This data," he says, "will be mined for a long time to come."

1 J. K. MacCarthy *et al.*, Seismic tomography of the Colorado Rocky Mountains upper mantle from CREST: Lithosphere-asthenosphere interactions and mantle support of topography. *Earth Planet. Sci. Lett.* **402**, 107–119 (2014).

2 C. Chen, D. Zhao, S. Wu, Crust and upper mantle structure of the New Madrid Seismic Zone: Insight into intraplate earthquakes. *Phys. Earth Planet. Inter.* **230**, 1–14 (2014).

3 A. M. Forte *et al.*, Descent of the ancient Farallon slab drives localized mantle flow below the New Madrid seismic zone. *Geophys. Res. Lett.* **34**, 1–5 (2007).

4 D. Zhao, Global tomographic images of mantle plumes and subducting slabs: Insight into deep Earth dynamics. *Phys. Earth Planet. Inter.* **146**, 3–34 (2004).

5 H.-H. Huang *et al.*, Volcanology. The Yellowstone magmatic system from the mantle plume to the upper crust. *Science* **348**, 773–776 (2015).

6 D. Zandomeneghi *et al.*, Internal structure of Erebus volcano, Antarctica imaged by high-resolution active-source seismic tomography and coda interferometry. *J. Geophys. Res. Solid Earth* **118**, 1067–1078 (2013).

7 C. Jiang *et al.*, Seismically anisotropic magma reservoirs underlying silicic calderas. *Geology* **46**, 727–730 (2018).

8 Y. Xu, K. D. Koper, R. Burlacu, Lakes as a source of short-period (0.5–2 s) microseisms. *J. Geophys. Res. Solid Earth* **122**, 8241–8256 (2017).

9 E. M. Berg *et al.*, Tomography of Southern California via Bayesian joint inversion of Rayleigh wave ellipticity and phase velocity from ambient noise cross-correlations. *J. Geophys. Res. Solid Earth* **123**, 9933–9949 (2018).