Down to work. Seismologists are continually transplanting their subterranean seismometers to paint a seismic image of the deep Earth.

GEOPHYSICS

Scoping Out Unseen Forces Shaping North America

As it sweeps across America, the USArray network of seismometers is revealing an impressive but often befuddling subsurface menagerie of slabs, drips, and plumes

Unlike geologists, who can reach only a few kilometers below Earth's surface, geophysicists routinely probe thousands of kilometers down in search of the ultimate forces that created and still shape the ground we tread. But so far, geophysicists' picture of Earth's interior has been maddeningly fuzzy. To sharpen it, they are scanning the deep subsurface as never before, pushing a fly's-eye-like network of seismometers across the lower 48 U.S. states. Researchers "are jumping up and down" with all the new data, says seismologist Edward Garnero of Arizona State University (ASU), Tempe. "We're pretty ecstatic."

And sometimes they're pretty bewildered. "There are so many [imaged] structures under the western U.S.," says seismologist Eugene Humphreys of the University of Oregon, Eugene. It's like "we just wandered into a dark room and someone turned on the lights. We're struggling to make sense of it." Clearly, the great blobs and chunks of rock rising, sinking, or just floating beneath the surface bear some relation to overlying mountains, basins, and volcanic outpourings, but even the avalanche of new data can't always resolve exactly what the imaged features are or how they are shaping the surface.

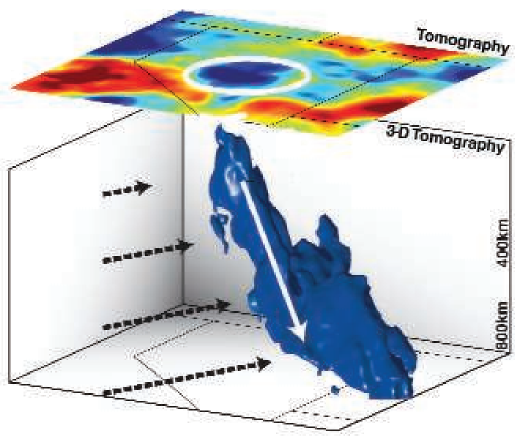
A creepy-crawler camera

The data surge comes courtesy of the U.S. National Science Foundation's (NSF's) $25-million-a-year EarthScope program, now early in its second 5-year run. EarthScope's three-pronged approach is creating an evolving three-dimensional picture of the North American continent. In one component, researchers drilled through the San Andreas fault (*Science*, 12 October 2007, p. 183). In the second, they are gauging the changing strain on the crust as it is deformed by deep stirrings and jostling tectonic plates.

EarthScope's third component—the $13.6-million-a-year USArray program—looks much deeper. The USArray system records seismic waves from distant earthquakes after they've passed through—and been altered by—the rock beneath North America. USArray involves three kinds of seismic networks: a Reference Network of 100 seismometers permanently installed 300 kilometers apart in a loose grid across the lower 48 states; a Flexible Array of 446 seismometers that are typically placed 10 kilometers or so apart for a few months or years to study a feature of particular interest; and the novel Transportable Array, an 800-kilometer-wide net of 400 advanced seismometers 70 kilometers apart.

The novelty of the Transportable Array is its combination of broad coverage, relatively dense instrument spacing, and mobility. The array started out hard against the West Coast in 2004 and has been steadily creeping eastward. Today its net spreads 2000 kilometers along the Rocky Mountains from the Canadian border to the Mexican border. Each month, about 18 instruments on the west side of the array that have collected a couple of years' worth of data are removed from their 2-meter-deep vaults and reinstalled on the east side. Reusing the equipment keeps the project affordable. Over the course of 10 or 12 years, the Transportable Array will occupy 1600 locations from coast to coast. Since 2004, all of USArray has generated 14.3 terabytes of data, nearly as much as the Global Seismographic Network has produced since 1988.

The more data collected and the more closely spaced the instruments, the sharper the pictures of the interior. The most heavily used seismic imaging technique—seismic tomography—works like a computed tomography (CT) scan of the human body. In a CT scan, different body parts absorb x-rays to different extents; in seismic tomography, it is rock's varying effect on the velocity of seismic waves that paints the picture. Waves pass through colder rock faster, for example—yielding a patch of blue in tomographic images—and through hotter rock more slowly, rendered as red.



What a drip! Seismic waves that are slower or faster than normal (blues or reds, *top*) can create a 3D image (blue, bottom) of a sinking "drip" tilted by "blowing" mantle rock (dashed arrows).

A deep zoo

For the first time, seismic tomographers are incorporating substantial amounts of USArray data into images of the deep western United States. Already, the new images have added fuel to a long-running debate over the existence of mantle plumes (*Science*, 22 September 2006, p. 1726). One contingent of researchers studying tomographic images had seen these

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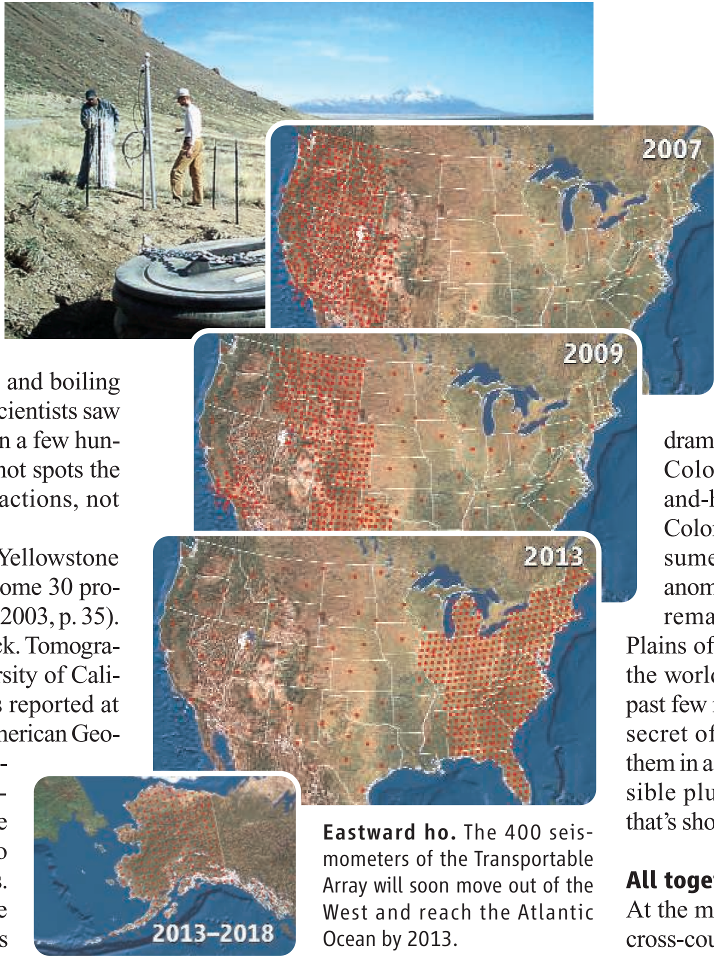
Published by AAAS



tall columns of hot rock rising thousands of kilometers from deep in the lower mantle like smoke from a stack. Where plumes reach the surface, those researchers say, the rising hot rock melts and feeds hot spots like the volcanoes of Hawaii or Iceland or the geysers and boiling pools of Yellowstone. But other scientists saw hot rock extending no deeper than a few hundred kilometers and considered hot spots the products of tectonic plate interactions, not heat from the deep interior.

The putative plume beneath Yellowstone was among the most suspect of some 30 proposed plumes (*Science*, 3 January 2003, p. 35). But with USArray it's coming back. Tomographer Richard Allen of the University of California, Berkeley, and colleagues reported at last December's meeting of the American Geophysical Union (AGU) that Transportable Array data add to evidence of a seismically slow zone beneath Yellowstone extending to a depth of at least 1000 kilometers.

Eastward ho. The 400 seismometers of the Transportable Array will soon move out of the West and reach the Atlantic Ocean by 2013.

"The whole history of mantle plumes makes you hesitate," says Allen. Still, he says, "I feel pretty confident about a plume to lower mantle depths." Unlike the bolt-upright columns geoscientists imagined when they first conceived of plumes in the 1970s, Allen says, his group's Yellowstone plume slants to the northwest through the upper mantle and balloons into a much broader slow zone below 660 kilometers in the lower mantle. It even seems to have torn the cold slab of oceanic plate sinking eastward through the upper mantle under the continent.

Other researchers, however, see different pictures. Seismologist Matthew Fouch of ASU Tempe agrees that there's "no clear evidence of a simple mantle plume" beneath Yellowstone. Rather than a contorted columnar plume, Fouch and colleagues say, their processed seismic data show a bent, thin "hot sheet" extending between shallow and deep blobs of hot rock. But when seismologist Rob van der Hilst of the Massachusetts Institute of Technology in Cambridge looks at his and others' tomographic images, he finds that "it's hard to say if [the hot feature] is continuous." Whether there's a single tall plume or a random series of unconnected blobs "is still up in the air," he says.

Some other creatures in the tomographic zoo are proving easier to interpret. Recognized decades ago, the Isabella Anomaly is a blob of rock lying 70 kilometers to 250 kilometers beneath the western edge of the Sierra Nevada mountains of central California. Seismic waves pass through it unusually fast, prompting speculation that it is denser due to the composition of its rock. That higher density might have made it fall away (or drip away, as geophysicists say) from the base of the Sierra Nevada. Relieved of that burden, the less dense crust could have floated up to form high mountains.

In part to test the Sierra Nevada drip idea, seismologists led by George Zandt of the University of Arizona, Tucson, superimposed the Flexible Array on the Transportable Array as it was passing over the Isabella Anomaly. The sharpened view showed a narrower anomaly than before, which allowed the group to calculate a density for the anomaly's rock. It turns out to be so dense that it must contain just the kind of rock hypothesized to have dripped away from the base of the Sierra Nevada, Zandt, William Levandowski of the University of Colorado (CU), Boulder, and the rest of the group reported at the AGU meeting. The group concludes that the drip could have triggered the Sierra Nevada's uplift.

Other seismic anomalies both fast and slow are now getting close looks in USArray data. In the June issue of *Nature Geoscience*, seismologist John West of ASU Tempe, Fouch, and colleagues reported that they had discovered a 500-kilometer-tall drip beneath south-central Nevada, tilted to the northeast by slowly flowing mantle rock "blowing" in that direction. The flow of the Great Basin Drip tugging on the crust would explain a mysterious patch of crust under compression amid the Great Basin's pervasive crustal extension, the group says, although others see mantle flowing around a slab fragment rather than a drip.

The Aspen Anomaly, a stretch of rock that slows seismic waves dramatically, sits directly beneath 80% of Colorado's 14,000-foot-(5100-meter)-and-higher peaks as well as the ore-rich Colorado Mineral Belt. Researchers presume there's a connection between the anomaly and the mineralized uplift, but it remains unproven. And the High Lava Plains of southeastern and central Oregon—the world's largest volcanic province of the past few million years—must be guarding the secret of their origins somewhere beneath them in a mix of sinking slab fragments, a possible plume tail, and flowing mantle rock that's showing up in the latest data.

All together now

At the midpoint of the Transportable Array's cross-country march, researchers wish USArray were yielding more insights and prompting less squabbling. "We're getting a clearer vision in the West," says van der Hilst, but "when you look at the details, people do see different things. The [tomographic] models allow for different interpretations." Fouch notes that with each group's different processing of the same data, "you can let tomography become a Rorschach test."

Researchers say they'll soon find better ways to interpret USArray observations. "It's such an unwieldy mass of data," says geophysicist Craig Jones of CU Boulder. "Playing with it is a different game than we're used to. I have a feeling we'll be seeing in the next 5 years analyses far more imaginative than what we've done so far." Some innovative new techniques are already on the horizon. For one, seismologists are starting to use background seismic noise generated by ocean waves—so-called ambient noise—to form tomographic images.

And then there are the geologists. EarthScope was originally supposed to bring geophysicists and geologists together (*Science*, 26 November 1999, p. 1655). Funding shortfalls early in EarthScope frustrated the marriage, but now NSF is managing to fund more geological work in and out of EarthScope. Relating geological traces at the surface to underlying seismic anomalies could help explain why there's such a weird assortment of still-active deep processes shaping the surface of the American West. **–RICHARD A. KERR**