Why the West Stands Tall

New geophysical research shows that the lofty peaks and plateaus of the American West are buoyed up not by the continental crust alone, but also by deeper forces from Earth's mantle

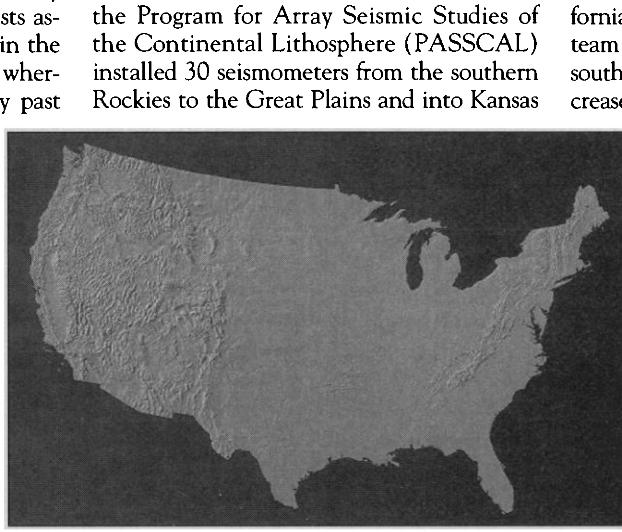
From California's Sierra Nevada east to the Rocky Mountains, the American West stands tall, making Denver the "Mile-High City" and raising the average altitude to 1.5 to 2.2 kilometers above sea level. But what keeps this landscape riding so high? In the Himalayas, a collision of continents forces up the mountains, but the American West is far from any collision zone. So for years, geophysicists assumed that the crust was its own law in the West, with high topography appearing wherever the crust had been thickened by past geologic events. But new glimpses of the West's underpinnings show that the crust alone isn't making mountains. It has a hidden partner, tens of kilometers down: the underlying mantle, which appears to be a vital player in lifting mountains all across the American West and probably elsewhere around the world.

"In the old days, people thought of mountain belts as a little like pushing a rug [the crust] on the floor and the rug crumples," says seismologist Walter Mooney of the U.S. Geological Survey in Menlo Park, California. "Now, we're seeing that you just can't get around including the mantle in the discussion." Geophysical surveys have recently shown that some of the West's most spectacular summits, including the southern Sierra Nevada and the southern Rocky Mountains, lack the thickened, buoyant "crustal roots" once thought to lift them to their present heights. The new work suggests that the mantle, which had been considered too uniform to affect topography, actually varies greatly from place to place, and that many mountain peaks in the West and elsewhere owe their height to increased warmth and buoyancy in mantle rock.

Surface topography, it seems, reflects the geological history of the underlying mantle as well as of the crust. "We're finally reaching the point of identifying geology in the upper mantle," says seismologist Craig Jones of the University of Colorado. "There's a lot going on; probably, the geology of the mantle is every bit as messed up as the geology of the surface."

Geophysicists knew that plenty of activity had to be going on somewhere under the western United States. Elevations in the American Cordillera, as geologists call the 2-million-square-kilometer plateau, range from the soaring mountains of the Sierra and Rockies to the lower but still high-standing Great Basin of Nevada, the Colorado Plateau, and the Columbia Plateau of Oregon (see map on p. 1565). To find out what's holding up all that spectacular scenery, geophysicists set out to map the thickness of the crust.

One such effort dates back to 1992, when the Program for Array Seismic Studies of the Continental Lithosphere (PASSCAL) installed 30 seismometers from the southern Rockies to the Great Plains and into Kansas and began recording seismic waves emitted by distant earthquakes. The speed at which the waves travel depends on the temperature, composition, and physical state—solid or melted—of the rock they pass through; for example, waves travel more slowly through the crust, which is less dense than the mantle.



G. THELIN, R. PIKE/USGS

Raising the mountains' roofs. The peaks and plateaus of the American West are lifted by hot, buoyant mantle far below.

In the first step of PASSCAL data analysis, seismologist Anne Sheehan of the University of Colorado and her colleagues reported in late 1995 that the crust, which has an average thickness of 35 kilometers in the eastern United States, thickens to 44 kilometers beneath the Kansas Great Plains and 50 kilometers beneath the Colorado Great Plains. That thickened crust is enough to float the High Plains and Denver to their heights, like the deeper keel of a larger iceberg. But the PASSCAL data show that the crust of the Rockies is also 50 kilometers thick—which means that the crust can't be responsible for the 2-kilometer jump in elevation from Denver to the Rockies. Instead, it must somehow be due to the mantle.

Meanwhile, on the other side of the Cordillera, seismologists using a different set of clues, including artificial seismic waves and variations in the Earth's magnetic field, searched beneath the 2800-meter peaks of the southern Sierra Nevada for a big crustal root. They too were surprised. "I was stunned to find high mountains were being held up by the mantle, not by a crustal root," says Mooney, a member of a team led by Brian Wernicke of the California Institute of Technology (Caltech). The team found that crustal thickening across the southern Sierra was minimal, although a decrease in crustal density from east to west can account for about a quarter of the uplift, says Jones, another member of the team whose study was published last year (*Science*, 12 January 1996, p. 190). The rest of the southern Sierran uplift, like that in the Rockies, must somehow stem from the mantle.

And the West is probably not alone among high regions in the skimpiness of its crust. Mooney and seismologist John Vidale of the University of California, Los Angeles, have completed a worldwide survey of crustal thickness based on seismic velocities reported in the literature. In a computer model, they "floated" that global crust on a model mantle of uniform density, to see where the crust alone could produce the observed topography. In Tibet, for example, the crust is 75 kilometers thick, double the average and thick enough to hold up the 5-kilometer-high plateau; the Andes are also self-supported. But at "the majority of other places on Earth, the topography simply cannot be explained by the crustal portion," says Mooney, who presented this work at the December meeting of the American Geophysical Union. And that, says seismologist Kenneth Dueker of the University of Colorado, suggests the mantle is holding up landscapes around the world.

Deep and ancient roots

But how, exactly, does the mantle create mountains? Deeper probing beneath the West is pointing to some answers. Using PASSCAL data, seismologists Duk-Kee Lee and Stephen Grand of the University of Texas, Austin, mapped out seismic velocity variations in three dimensions as deep as 350 kilometers beneath the Rockies. In last October's *Journal of Geophysical Research*, they reported that, between Kansas and the Rockies, seismic velocities drop by a whopping 9% in the upper

Is a Great Plateau Slip-Sliding Away?

The hot, buoyant mantle beneath the American West helps give it a lofty perch (see main text)—but not a secure one. Other high parts of the world, such as the Himalayas, have colliding continents to squeeze them upward, but the West, floating on its own, is slowly spreading outward. But where's a continent to go? Hemmed in on most sides by rigid tectonic plates, this one may be heading for the Pacific Northwest, where plate motions open a small escape hatch.

"If you're part of high-standing North America and you want to get out, that's your only shot at it," says geophysicist Eugene Humphreys of the University of Oregon, who with Mark Himphill-Haley of UO is tracing the continent's path to freedom. If they can show just how it works, they may be able to explain some otherwise cryptic geology in the Northwest.

Geophysicists measuring the slowly changing distances between points on the surface have already mapped part of the high West's possible escape route. These measurements, made with high-precision techniques such as very long baseline interferometry (VLBI) that use the radio emissions of quasars as benchmarks, show little sign of movement at the Colorado Plateau, says Humphreys. But at Ely, in eastern Nevada, the land is moving westward at 5 millimeters per year. From there, westward across Nevada's corrugated Basin and Range, Humphreys infers that the land is sliding from the heights supported by the hot, buoyant mantle.

In Humphreys's view, this push from the east helps to create some California scenery. "There's nothing continuing to hold the interior together, so it is pushing the Sierra Nevada and crunching up the crust along the San Andreas," he says. That's the reverse of the conventional view, which holds that it's the Pacific Plate pushing from the west that shoves up the Coast Range along the length of California.

But the Sierra Nevada themselves aren't going along for the ride, notes Humphreys. VLBI data show that they are moving not to the west but to the northwest, apparently sliding along a branch fault of the San Andreas in parallel with the Pacific Plate on the other side of the great fault. The reason for this change in direction, says Humphreys, is that "the Pacific Plate is in the way. You can't just run over it."

Finding no outlet to the west, the land finds "a hole to flow out of in the Pacific Northwest," as Humphreys has argued in recent talks. The hole lies in the northeastern Pacific, north of the Pacific Plate, where the Juan de Fuca Plate dives out of the way beneath Oregon, Washington, and British Columbia.

Proving this notion is difficult, however, because in the Pacific Northwest, the geodetic data peter out. Instead, Humphreys must look to the origin of cryptic geological features. He cites the east-west orientations of such features as the Yakima fold and thrust belt of central Washington, where the crust has been crumpled along a north-south axis, as evidence of past crustal motion toward this "tectonic window."

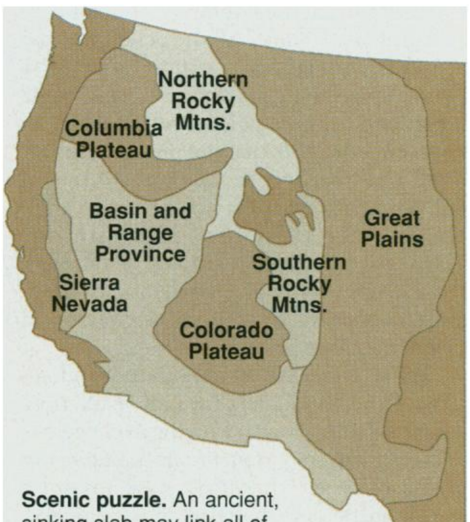
Pacific Northwest geologists are still digesting Humphreys's ideas. "I'm delighted at the broad picture he's painting," says Ralph Haugerud of the U.S. Geological Survey at the University of Washington. "But I don't know how much truth there is in it." Haugerud wants more time to compare Humphreys's predictions with the geology he knows. And time he has. The Pacific Plate's stately march northwestward along the San Andreas is closing the tectonic escape hatch, but if Humphreys is right, the continent will have a bit of room to roam for millions of years. **–R.A.K.**

200 kilometers of the mantle.

Such a drastic slowdown could only be produced by conditions very different from those found in the relatively cool and therefore dense mantle that lies just beneath most continents. The slowdown implies a combination of both high temperatures and partial melting of the rock, Lee and Grand concluded. They calculated that about 1.5% of the upper mantle rock beneath the Rockies is melted into thin crack-filling films. Together with the high temperature, the melting would reduce the mantle's density by 1%, the amount needed to buoy the Rockies above the High Plains.

In the Sierra, too, Wernicke and his colleagues judge that buoyant mantle has replaced normal mantle, at least beneath the highest, eastern part of the range. They suspect that the Sierra also get a boost from a secondary effect of the high temperatures: a change in mineral structure in the upper mantle. Minerals dredged from the mantle by magma that has risen into the eastern Sierra show that heat has transformed the dense mineral garnet into a less dense crystal form, according to work by geologists Jason Saleeby and Mihai Ducea of Caltech. That change would help uplift the mountains, says tectonophysicist Eugene Humphreys of the University of Oregon.

As to why the mantle beneath so much of the West is buoyant, Grand points out that the Rockies' mantle, like the mantle just to the south beneath the Rio Grande Rift of New Mexico, resembles the hot, soft mantle that normally lies deep beneath plates and rises only at volcanic midocean ridges. The new work suggests, say Grand and others, that all along the broadening rift, in the southern Rockies,



Scenic puzzle. An ancient, sinking slab may link all of the West's complex mountain ranges and plateaus.

and under the eastern Sierra, this hot, weak layer of the asthenosphere has welled up.

Its rise, geologists speculate, might somehow be ultimately due to one ancient event that ties this hodgepodge of geologic provinces together: the thrusting of an oceanic plate called the Farallon eastward beneath what is now the western United States about 65 million years ago. Oceanic plates usually dive steeply into the mantle, but a burst of volcanism and other geologic signs across the West suggest that the Farallon Plate scraped horizontally against the underside of the continental plate instead, making the U.S. Cordillera tectonically "alive" today, says Humphreys.

Just how the slab left the overlying mantle altered isn't known, but there are plenty of options, says Grand. The slab could have infused mantle rock with water and so lowered the melting point, or simply have drawn up hot asthenosphere from below as it finally fell back down into the mantle. But even if the Farallon's exact role in creating the West's current stature is not clear, geophysicists are realizing that the history of the underlying mantle can no longer be overlooked. When it comes to topography in the American West and perhaps elsewhere, the mantle helps lay down the law of the land.

–Richard A. Kerr