Making Mountains with Lithospheric Drips

The rigid underpinnings of several western states may have dribbled away, raising mountains as the drips passed by

To look at Mount Whitney and the other snow-capped peaks of the High Sierra, soaring 3000 meters from the floor of California's Owens Valley, one would suppose that they are up there because they are underlain by the usual buttressing found beneath mountains; strong, deep foundations would seem to be called for.

But in a proposed mechanism for holding up these and other mountains, the usual support is missing. Tens of kilometers of rock strengthened by its low temperature have dripped away from the crust to be replaced by hotter rock whose inherent buoyancy has shoved the High Sierra upward. According to this hypothesis, ripples of such mountain building would have been spreading across the American West during the past 30 million years, leaving the jumbled terrain of Nevada and surrounding states in their wake.

The globs of relatively cold rock dropping hundreds of kilometers into the mantle that should precede this wave of mountain building are beginning to show up. The key to their detection has been the combining of large numbers of seismic records from distant earthquakes whose waves had passed through the upper mantle on their way to the surface. Such a summation of data was made possible by the same technique that allows medical researchers to make computer-assisted tomography or CAT scans, the three-dimensional x-ray images of the human body.

In 1984, Eugene Humphreys of the University of Oregon and Robert Clayton and Bradford Hager of the California Institute of Technology were the first to use seismic waves from distant earthquakes, the equivalent of the x-rays, recorded at closely spaced seismograph stations, the x-ray detectors, to form a detailed tomographic image of the deep earth directly beneath a seismic network. Rather than indicating the degree of absorption, as do x-ray images, seismic tomographic images reveal how the velocity of seismic waves varies. Hotter rock, for example, slows waves down, and colder rock speeds them up.

Humphreys and his colleagues developed a tomographic image of a 500-kilometer-deep block beneath southern California from 10,000 crisscrossing paths between earthquakes around the globe and the 200 stations of the Southern California Array. The varying transit times along those paths combined to form an image of a narrow, 250-kilometer-deep tongue of relatively cold rock (*Science*, 17 August 1984, p. 702). Having seismic velocities about 3% faster than its surroundings, the rock is probably about 400°C colder than the rest of the region. Intriguingly, the cold, slablike protrusion extends directly beneath the Transverse Ranges, the linear string of mountains running along the east-west jog or Big Bend of the San Andreas fault just north of the Los Angeles basin.

By analyzing earthquake records from other seismic networks, Humphreys and his students at Oregon are finding more globs of anomalously cold rock dripping into the mantle. Most of these networks, like the Southern California Array, were intended to monitor nearby, potentially dangerous faults. None of the networks provides images as sharp and reliable as that beneath southern California, but the features appear to be real enough.

The most well-defined anomaly lies just to the west of the High Sierra, beneath the foothills of the Sierra and the Great Valley that runs down the middle of California. Seismic waves passing through the anomaly arrive 0.7 second earlier than they would otherwise, as was the case for the Transverse Ranges anomaly. The southern Sierra anomaly has similar dimensions to that 200 kilometers to the south, extending as it does 300 kilometers from the surface and running almost 250 kilometers parallel to the mountains. A slow, presumably warm anomaly extends eastward from the foothills, under the Sierra, and out beneath the valley and ridge terrain of the Great Basin at least as far as the Nevada border.

There are other anomalies around the Great Basin. On the other side of it in northern Utah, a fast anomaly extends to a depth of about 200 kilometers just outside the eastern wall of the basin formed by the still-rising mountains of the Wasatch Front. On the north, an anomaly underlies the growing Wallowa Mountains.

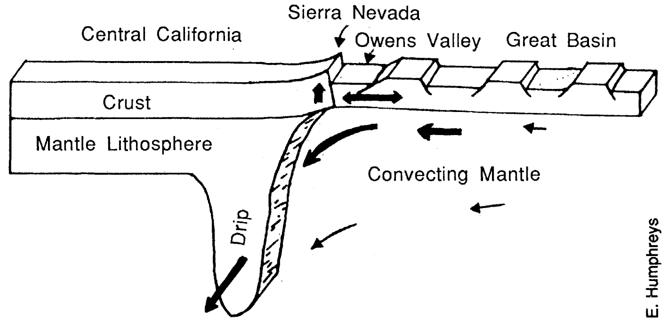
To Humphreys, the close association of seismic anomalies and mountains implies that the formation of anomalies is involved in pushing up the mountains. In the case of the Transverse Ranges, there is general agreement among authorities as to the forces that are directly responsible for building the mountains. The plate to the west of the San Andreas, which carries Southern California, is moving northwestward several centimeters per year. But the Big Bend lies squarely in its path, so some of the southern plate's crust is scraped off by the encroaching northern plate. The compressed pile of crust forms the mountains, which are held up largely by the strength of the plate beneath them.

Opinion diverges when geophysicists consider the fate of the subcrustal portion of the plate, which is also called the mantle lithosphere. This is the chemically distinct rock, immediately below the 20- to 40-kilometer-thick crust, that along with the crust has chilled enough to form a single, relatively rigid plate or lithosphere. Below the plate the rest of the mantle slowly churns as its colder, denser portions sink and its hotter, more buoyant portions rise.

The combined effect of the mantle lithosphere's composition and low temperature make it dense enough, about 1% more dense, to participate in mantle convection, if only its chilling had not also made it so viscous and rigid. It can eventually chill too

The Sierran drip

Once something disturbed the dense but viscous mantle lithosphere, it could dribble into the mantle, drawing in hot mantle. Its buoyancy would then raise the Sierra Nevada. The drag of the convecting mantle would stretch and break the adjacent crust.



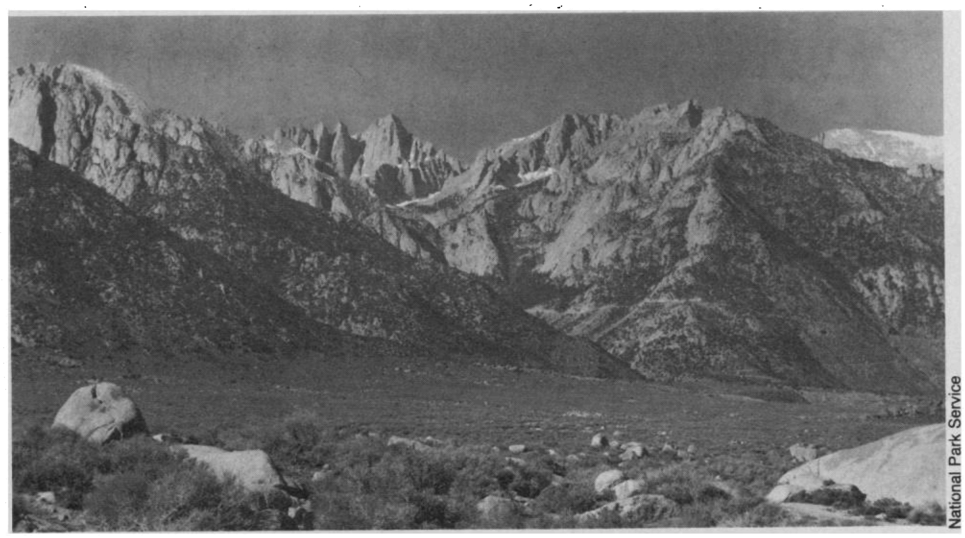
much, become unstable, and fall away on its own, but otherwise a strong disturbance would be needed to destabilize it.

On the basis of the subtle variations of gravity across the Transverse Ranges, Barbara Sheffels and Marcia McNutt of the Massachusetts Institute of Technology concluded that encountering the Big Bend is enough of a disturbance to send the northward-moving mantle lithosphere plunging into the mantle as an intact slab, much as the Pacific plate dives beneath the coast of Japan. The seismic anomaly is simply that descending slab, according to this thinking.

What Sheffels and McNutt call a slab, Humphreys would call a drip. But there is more than a semantic difference. Although in both cases lithosphere with nowhere else to go is sinking under its own weight, Humphreys sees a central role for mantle convection. The plate segment that is running into the Big Bend would seem to require some help in continuing to move northward during the past few million years, says Humphreys. The help could come from mantle circulation. Once begun, a convection cell having a rising arm near the southern end of the San Andreas, beneath the Gulf of California, would flow northward, dragging the plate with it. The sinking of the drip itself, which would be fed dense lithosphere from both north and south, would provide the driving force of convection. Thus, the Big Bend and the Transverse Ranges exist because the drip exists, according to Humphreys.

Humphreys and his colleagues envision a different cause and effect relation between drips and mountains around the edge of the Great Basin. There the dribbling away of mantle lithosphere would draw in hot, convecting mantle behind it. The replacement of cold, dense lithosphere with hot, buoyant mantle would push up mountains. The sharp suction beneath the crust at the trailing edge of the drip would stretch the crust just beyond the mountains. If the drip were propagating from east to west, high mountains with no obvious means of support would lie to the east of a deep, cold seismic anomaly and to the west of relatively elevated crust stretched to the point of breaking into blocks. The mantle lithosphere would be missing east of the drip. That is what Humphreys believes he sees across the southern Sierra Nevada.

The problem of what holds up the southern Sierra Nevada has presented a quandary for decades. The usual means of building mountains is to have plate motions shove them onto a strong plate, as in the case of the Transverse Ranges or the Himalayas, or to create a deep root of light crustal rock that floats the mountains the way the unseen bulk of an iceberg floats it. A root, such as the one that extends 70 kilometers beneath the Andes, can form when volcanic magma rises into the crust to form less dense intrusions or when compression squeezes crust downward. All of these mountain building mechanisms involve the convergence of two plates—an outright collision or the sinking of one beneath the other.



Could Mount Whitney be floating on hot mantle? *The High Sierra in Sequoia National Park, including 5-kilometer-high Mount Whitney viewed here from the Owens Valley, rose more than 2 kilometers during the past 10 million years although there is no sign of the usual mountain-building forces being at work. A new proposal suggests that the replacement of cold mantle with hot beneath these mountains sent them upward.*

The problem is that the 4-kilometer-high southern Sierra Nevada has risen more than 2 kilometers since 10 million years ago, but no plates have converged near there for more than 70 million years. Clement Chase and Terry Wallace of the University of Arizona resolve that quandary by assuming that a buoyant root formed more than 70 million years ago, raised high mountains, and then became locked into a thick, rigid lithosphere as the region cooled. Much of the mountains eroded away, but the newly unburdened root could not rise until extension of the crust snapped through the lithosphere beneath the Owens Valley to the east, Chase and Wallace suggest. Once released, the previously restrained buoyancy of the root could float the Sierras to their present height. The existence of a Sierran crustal root has been suggested on the basis of seismic probing from the surface, but its size is debated.

Craig Jones of Caltech raises the southern Sierras by having the lithosphere thinned beneath them, as Humphreys prefers, but the thinning is accomplished by extension that slices a fault not only through the crust but deep into the lithosphere. As suggested for other locations by Brian Wernicke of Harvard University, slip on such a fault diving beneath the Sierras from the east could produce the jumble of crustal blocks that typifies the valleys and ridges of the Great Basin as well as thin the lithosphere beneath the High Sierra.

Humphreys sees no need for a crustal root or a lithospheric fault. In his model, the Sierran seismic anomaly is one drip of many that began sloughing off mantle lithosphere at a speed of roughly 2 centimeters per year. The initial extension and rifting of the lithosphere 30 million years ago would have gotten it all started by placing hot mantle in the center of the rift next to cold lithospheric mantle, an inherently unstable arrangement. The rifting would have sent drips marching outward the way a rock dropped in a pond creates ripples.

The encouraging aspect of the Sierra Nevada problem is that it is testable. Better seismic surveys should pin down the size of any root. Geologic work should suggest whether a wave of mountain building followed by subsidence approached from the east. But expanding the search for drips will be hampered by the limitations inherent in appropriating data intended for other purposes—the observations will never be as abundant or as uniformly distributed as seismologists would like.

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ADDITIONAL READING

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