Earth's Surface May Move Itself

Realistic models of Earth's shifting plates strengthen the case that the tug of old ocean floor sinking into deep trenches is what powers most plate motions

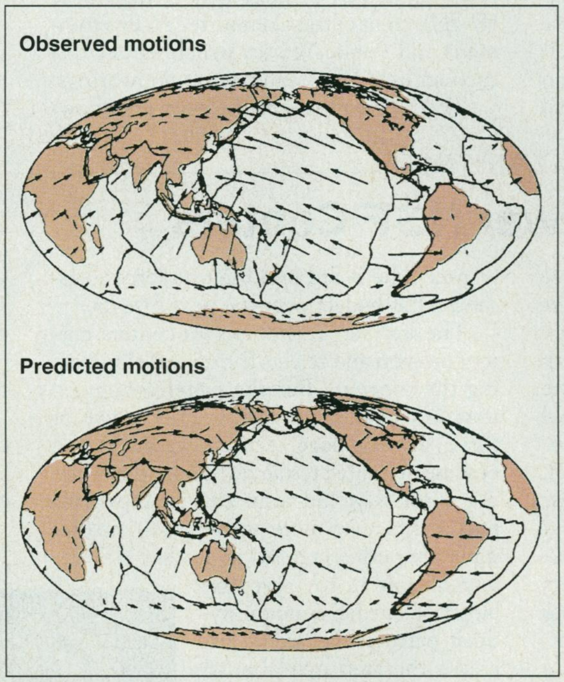
The realization more than 25 years ago that every spot on the planet's surface is moving shook up geophysics and geology—and dispelled a host of mysteries. The Himalayas rose because India is slamming into Asia; the earthquakes common around the Pacific Rim take place because slabs of ocean floor are slipping into the mantle at deep-sea trenches; and the strange ridges that wind through the world's oceans are the geologic wounds where the crust is spreading apart.

But in spite of all the mysteries this picture of moving tectonic plates has solved, it has a central, unsolved mystery of its own: What drives the plates in the first place? "[That] has got to be one of the more fundamental problems in plate tectonics," notes geodynamicist Richard O'Connell of Harvard University. "It's interesting it has stayed around so long." Judging by recent work, though, it won't stay around forever.

On one level, why the plates move is no mystery at all. Plates are just the upper limb of a vast, heat-driven circulation system that stirs the planet to its depths. But pinpointing where the forces that actually move the plates are concentrated has been difficult, given researchers' fuzzy view of Earth's interior and the limited ability of computer models to simulate the planet's complex dynamics. Now the most realistic computer models of plate motions to date have strengthened the case for one of the front-running driving forces. Says Mark Richards of the University of California, Berkeley, who helped develop one of the models, "We tried to show clearly that the main driving force is slabs," churning the mantle as they sink into trenches and thus dragging the plates along.

Other researchers agree that the modelers have strengthened the case for slab pull. Even if these simulations hold up, however, they don't solve the full mystery of plate motions. At the same time as the computer models support slab pull, one group of researchers is saying that peculiar stirrings of the mantle beneath South America imply a different driving force in that part of the world (see story on p. 1215). And Richards notes that he and his fellow modelers still can't explain a mystery related to the plate-driving problem: Why plates in the real world suddenly change direction at intervals of tens of millions of years.

At least the field of candidate driving forces may be narrowing. Besides slab pull, researchers have been considering two others: drag from the flow of the uppermost mantle, which could shift the plates much as boiling water roils a scum-covered surface, or a push delivered by newly formed oceanic plate as it slides off the midocean ridge where it formed. Or perhaps some combination of mantle drag, ridge push, and slab pull is at work.



SOURCE: C. LITHGOW-BERTELLONI AND M. RICHARDS

Shifty planet. A model's simulation of plate motions over the last 10 million years *(bottom)* matches real plate motions deduced from the geologic record fairly well.

In most attempts to find out which driving force predominates, researchers have built models that start with assumptions about what the driving forces are and where they operate. They then run the models to see whether the simulated plates move in the right directions at the right speeds. These empirical models have tended to point to slab pull as the strongest force moving the plates. But earth scientists don't regard those results as conclusive, in part because the models generally include simplifications that may be unrealistic. One is the assumption that as slabs sink into the mantle, they pull only on the leading edges of plates, rather than setting up a circulation in the viscous mantle rock that would tug the plates over a broader area.

Researchers would much rather build a more realistic Earth model that can generate its own driving forces based on the interplay of gravity, density, mantle viscosity, and other factors. In 1981 Bradford Hager of the Massachusetts Institute of Technology and O'Connell used present-day plate arrangements to build the first such model. The model included a circulating mantle and simulated the actual physical processes of plate motion—crust sliding away from ridges and slabs sinking, stirring the mantle as they go. It then calculated the contribution of each of the three driving forces. The result: Slab pull and ridge push both seemed to be at work.

Now two groups—Richards and Carolina Lithgow-Bertelloni of the University of Göttingen, Germany, and, independently, Vincent Deparis of the University of Strasbourg, France, and his colleagues—have extended this approach to take advantage of improved knowledge of past plate motions. They built physical models of Earth that generated their own plate-driving forces, then tested their realism by applying them to the various configurations of plates that existed as much as 200 million years ago. Guided by reconstructions of trench positions from the geologic record, the modelers sank slabs into their models' mantle. They then allowed the plates to move and compared the results with geologically determined motions.

In both models, the plate motions closely matched the geologic record at a half-dozen times in the past. And in both cases, slab pull seemed to be the dominant driving force. When Lithgow-Bertelloni and Richards separated the effects of slab pull and ridge push, for instance, they found that the model slabs accounted for 95% of the net driving force. Ridge push came in at 5%. Slabs seem to owe their effectiveness, says Richards, to their ability to drag on the mantle as well as the leading edge of the plate.

"I think [the outcome] confirms the basic results" of earlier models, says Sean Solomon of the Carnegie Institution of Washington's Department of Terrestrial Magnetism, noting that the new models' realism makes the case for slab pull more persuasive. But

Solomon, O'Connell, and others are quick to point out that the models don't match reality perfectly. At times they generate unrealistically high stresses within the model plates or stretch the plates when the geologic evidence suggests they should be under compression. And the models don't simulate the behavior of plate boundaries other than ridges and trenches.

That's a major shortcoming, say Richards, Deparis, and others, because these boundaries may be the key to understanding what steers the plates. "The great mystery," says Richards, "is what forces of resistance are modulating the motions of the plates." Plates can keep moving in the same direction for tens of millions of years only to change course suddenly, as the Pacific plate did 43 million years ago, when its heading changed by 60° in about 1 million years. Because the mantle is so viscous, descending slabs could hardly shift their position that quickly. But another kind of boundary could explain this pattern of long stability followed by abrupt change, says Richards: transform faults such as the San Andreas fault, where plates slide past each other.

Such transform boundaries could act as "tongue-and-groove" guides, suggest Richards and Dave Engebretson of Western Washington University in Bellingham, allowing easy motion in one direction but resisting any shift away from that direction. If the slowly changing pull of a slab or the growing resistance due to a collision between one plate and another pushed a transform fault to the point of failure, however, one of the two plates might dive under the other, and the transform fault could turn into a new trench. Such an abrupt change in motion from along a boundary to across it could have led to the Pacific plate's sudden course change, says Richards: "I just don't know which transform fault did it."

Current models can't simulate that kind of behavior, but still more realistic model Earths might give Richards his answer. They will have to simulate both the churning of the mantle and the behavior of the brittle plate boundaries, including transform faults—and that will take both increased computing power and new modeling techniques. Until then, the puzzle of the plates will have a missing piece. "Until we have a model that reproduces" the complexity of reorganizing plates, says O'Connell, "we really won't understand the forces driving them."

–Richard A. Kerr

Additional Reading

V. Deparis, H. Legros, and Y. Ricard, "Mass anomalies due to subducted slabs and simulations of plate motion since 200 My," *Phys. Earth Planet. Interiors* **89**, 271 (1995).
C. Lithgow-Bertelloni and M. A. Richards, "Cenozoic plate driving forces," *Geophys. Res. Letts.* **22**, 1317 (1995).

. . . But Did Deeper Forces Act To Uplift the Andes?

The Andes shouldn't be there. Plate tectonics makes the world's great mountain ranges by slamming two continents together, as Europe collided with Africa to make the Alps or India ran into Asia to make the Himalayas. South America, however, is colliding with nothing more than the floor of the Pacific Ocean, which is slipping beneath the continent into Earth's interior. Such encounters between continent and ocean ordinarily throw up a few volcanoes, not a 7000-kilometer-long wall of mountains. But Paul Silver of the Carnegie Institution of Washington's Department of Terrestrial Magnetism (DTM) and his colleagues believe that by seismically probing deep beneath South America, they have stumbled on the answer to the origin of the Andes.

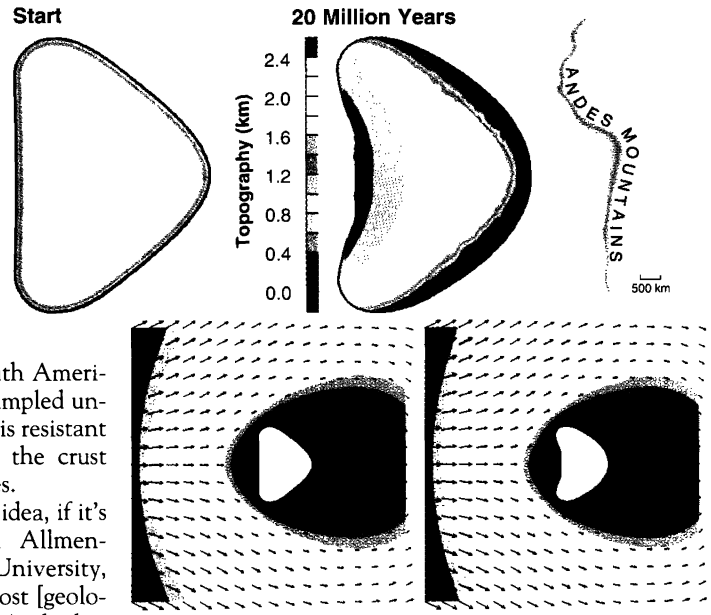
South America, they say, is driving westward so forcefully that the base of the continent is colliding with an unseen partner: the viscous mantle rock hundreds of kilometers down under the floor of the Pacific. Like a snub-nosed boat driven too fast for the strength of its hull, the central South American coastline has crumpled under the pressure of this resistant medium, thickening the crust and raising the Andes.

"It's a fascinating idea, if it's true," says Richard Allmendinger of Cornell University, "but I don't think most [geologists] working in the Andes believe it." Still, says seismologist Susan Beck of the University of Arizona, "whether [Silver and colleagues are] right or not, it sure generates a lot of interest."

Silver, who has been talking up the idea at recent geophysics meetings, isn't discouraged by the skepticism. Just for good measure, he recently extended the concept to North America as well, where the broad high country in the west has also long presented a conundrum. And he is invoking yet another unconventional idea to explain why South America is hurrying westward in the first place: It's being dragged by a current of mantle rock flowing beneath the continent. That's contrary to conventional thinking, which holds that plates drive themselves, largely by sinking into Earth's interior at the end of their lifetime (see story on p. 1214).

These unorthodox notions started to take root when tectonophysicist Raymond Russo of the University of Montpellier in France and seismologist Silver applied an emerging seismic technique for plotting mantle flow to the region west of South America. Flow in the upper mantle tends to line up mineral crystals in the rock to create a "grain," like the grain of wood. That grain can split a seismic shear wave—a wave that vibrates rock from side to side along its direction of travel—into two, because shear waves have two components that have different speeds along a rock's grain. Russo and Silver were able to use this shear-wave splitting to plot the flow of Pacific mantle where the floor of the Pacific is diving under South America.

According to theory, such subducting plates carry the surrounding mantle down with them. If so, the mantle to the west of the subducting plate should have been moving eastward and downward, with the plate. But as Russo and Silver reported a year ago in



SOURCE: L. P. SOLHEIM AND P. SILVER

The big push. In a computer model, mantle rock flowing into a triangular "continent" for 20 million years *(bottom)* pushes up an Andes-like mountain chain *(top)*.