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

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

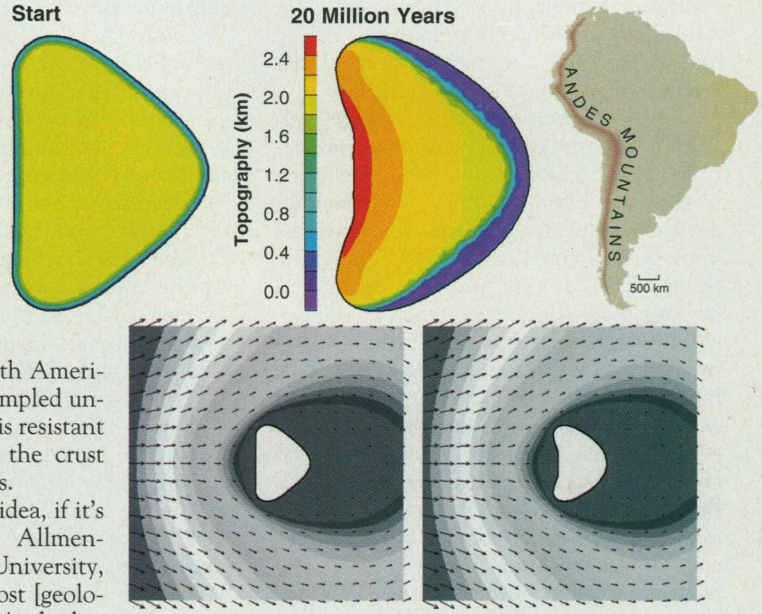
The Andes shouldn't be there. Plate tectonics makes the world's great mountain ranges by slamming two continents together, as Europe collided with Africa to make the Alps or India ran into Asia to make the Himalayas. South America, however, is colliding with nothing more than the floor of the Pacific 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.



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)*.

SOURCE: L. P. SOLHEIM AND P. SILVER

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

Science, they saw evidence that the mantle was moving perpendicular to the plate's motion instead—diverging at about the midpoint of the South American coast and flowing to the north and south.

To explain this odd flow pattern, Silver and Russo invoked South America's westward movement of 3.5 centimeters a year. As the curtain of descending oceanic plate retreats westward before the advancing continent, they and others have noted, it shrinks the space for mantle rock beneath it. The resulting excess mantle, Russo and Silver argued, flows laterally like a bow wave on a very broad ship. Where this ponderous bow wave finally clears the continent far to the north and south, it creates a wake, which can be seen as the swirl of small plates driving eastward off Cape Horn and in the Caribbean.

On South America itself, meanwhile, Russo and Silver suggested that the pressure of the mantle bow wave, transmitted through the descending ocean plate to the adjacent continent, might have pushed up the Andes. The mantle should exert the highest pressure where it backs up at the central coast before flowing north and south. And that's just where the coast has a deep indentation and the highest part of the Andes, called the Altiplano, has risen.

Geologists were doubtful. "I agree with Paul that a lot of the conventional explanations in plate tectonics aren't really sufficient to drive mountain-building," says seismologist Dean Whitman of Florida International University, "but I think he's stretching things too far. It's not entirely clear to me," he says, that you can connect mountain-building in the uppermost 100 kilometers of the South American plate and mantle flow hundreds of kilometers below, on the other side of the subducting ocean plate.

And some geophysicists weren't even convinced that the mantle bow wave exists. Beck, who also works in the area, thinks the mantle flow there "is looking more complicated [than Russo and Silver suggest]. The basic observation of shear-wave splitting is important, but what that means physically is difficult to say." Mantle rock is so viscous, adds Michael Gurnis of the California Institute of Technology, that a subducting plate has to carry it along; north-south flow across the direction of plate motion "seems implausible; it's just a weird model."

Silver has gone back to South America with portable seismographs to take a closer look. He believes that although some mantle may be dragged down with the slab, it still "looks for the most part like trench-parallel flow." And geophysical modeler Larry P. Solheim of DTM, with Silver, has used a simple computer model to test the idea that such flow could raise the Andes. They simulated a triangular continent plowing broadside into mantle with the subducting plate between them. In the model, the relatively rigid subducting plate transmits the pressure in the deep oceanic mantle to the continent's leading edge. That pushes in the central coastline and uplifts the model continent's coast from end to end. The uplift is most dramatic right at the bend—just where the Altiplano is found.

The model's success has led Silver to speculate about what could be driving this process in the first place by pushing South America to the west. One widely accepted driving force of plate motions—the pull of sinking slabs—doesn't work for South America, he notes, because its plate has no subducting edge. Some researchers have invoked a push from the eastern part of the plate, where newborn crust slides off the midocean ridge in the Atlantic, but Silver says that push falls far short of what's needed to raise the Andes. "You need some other force," he says, "and with South America there's not much else to appeal to except westward deep-mantle flow." The mantle beneath the Atlantic must be flowing westward as part of a deep circulation loop, dragging along the continent.

South America is the clearest example of tectonics powered by mantle flow, Silver says, but "what holds for South America probably holds for North America." It too lacks a subducting edge and has high ground along its western edge, which was bordered by a deep-sea trench for much of recent geologic history, and it too is moving westward. To Silver, that implies much the same mountain-building scenario as he and Russo have constructed for South America. "Here you have a mountain range that goes all the way from the Arctic to the Antarctic that people are still arguing about," says Silver. "This explains it."

And he isn't stopping there. He goes on to propose that mantle upwelling beneath the mid-Atlantic spreading ridge could diverge to drag Africa and Eurasia eastward even as it drags the Americas westward. Says Silver, "It looks like the Atlantic half of the world has continents that are being actively driven by deep-mantle flow," while the Pacific half is driven by subduction of oceanic plates.

Having explained the behavior of half the globe starting with a few split waves on a seismogram, Silver and his colleagues will have to do a lot more to convince seismologists, geologists, and geodynamicists that they've got it right. For now, though, "everything just works out," says Silver.

–Richard A. Kerr

Additional Reading

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BEHAVIORAL ECOLOGY

Cowardly Lions Confound Cooperation Theory

SERENGETI NATIONAL PARK, TANZANIA—A pride of female lions chasing an invading lioness out of its territory may look as single-minded and bent on retribution as a posse hot on the trail of a bank robber. But, on careful observation, the pride's character is as mixed as that of the citizens in the movie *High Noon*: stout-hearted Gary Coopers paired with outright cowards.

The existence of true lionhearts and cowardly lions, however, is not what has scientists excited about these observations of lions in Tanzania's Serengeti National Park and Ngorongoro Crater. What's causing a stir about the Report by Robert Heinsohn from the Australian National University and Craig Packer from the University of Minnesota, on page 1260 of this issue, is the lions' consistency. Lionhearted individuals are always brave, putting their lives on the line to defend their pride's territory, even if they are forced time and again to share defensive duties with a coward. And that throws a big monkey wrench into a classic explanation for the evolution of cooperative behavior in a selfish, dog-eat-dog (or lion-eat-gazelle) world.

"That's the big issue: Why will an animal do something that is a cost to itself and a benefit to others," says Luc-Alain Giraldeau, a behavioral ecologist at Concordia University in Montréal, Québec. "This study shows that the traditional approach to that question is flawed." That approach, based on theoretical models of interactions, suggests that cooperation can arise if animals react to one another's previous behavior: Cooperative actions beget more cooperation, while selfishness only gives rise to selfishness. But in some lions, selflessness comes to the fore regardless. Says Steven Lima, a behavioral ecologist at Indiana State University, "As the lions and empirical studies of other animals show, the models simply don't capture the essence of what's going on in the natural world. It's time there was a reality check."

Since the 1980s, biologists have attempted to understand the costs and benefits underlying animal cooperation by using various models from game theory, a branch of science largely developed by economists attempting to explain market decisions by hu-