GEOPHYSICS

The unfathomed forces driving earth's plates

Forces and processes in mantle causing extensive horizontal motions of earth's surface are still a puzzle to science

by Kendrick Frazier

The suggestion that the surface of the earth is mobile on a long time scale has now virtually won its long, uphill battle toward scientific acceptance and respectability. As Dr. Egon Orowan of the Massachusetts Institute of Technology puts it, "Altogether the polemics on continental drift are a sobering antidote to human self-confidence. Practically all arguments against it, and many for it . . . now appear to have been fallacious."

Despite their lack of full understanding, the tectonic theory they accept is enabling geologists and geophysicists to piece together a rough picture of horizontal movements over tens of millions of years, which have shaped the ocean basins, squeezed up the mountain belts and molded the continents.

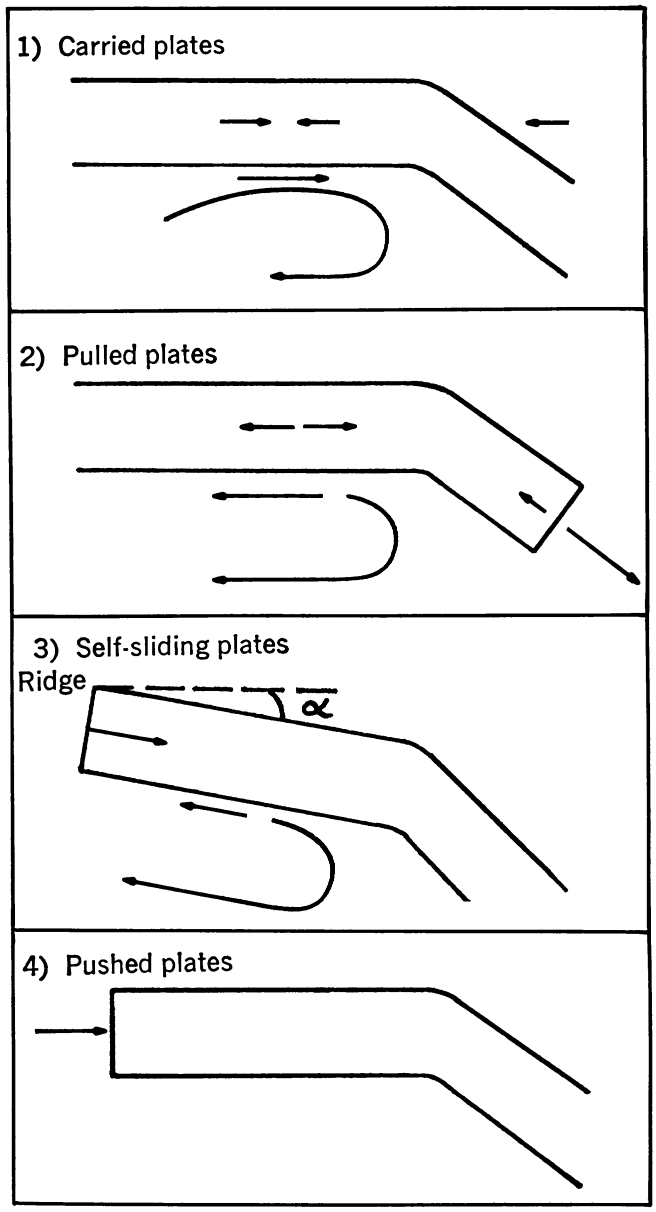
They are sure of their theory from evidence detectable on and near the surface. But the underlying forces responsible for the motions are still a puzzle. It is a matter of geophysical science knowing the what, but not the why and the how.

Here one enters into a kind of never-never land, where controversy is great, speculation rampant and information sparse. Explanations depend upon understanding forces and conditions deep within the earth's mantle and the ways in which energy there is converted to mechanical movement at the surface. That level of understanding is not yet at hand.

Knowledge about the mantle must be gained indirectly, from monitoring deep earthquakes, from laboratory simulations of the behavior of rock under high temperatures and pressures and from theoretical calculations.

The only unambiguous evidence for motions deep within the mantle is the occurrence of earthquakes as much as 700 kilometers beneath island arcs. All other observations are of movements of the lithosphere—the 70-kilometer-thick rigid layer of crust and upper mantle sectioned into slabs that move about over the softer part of the mantle like ice sheets floating over water. It is difficult to relate these surface movements to motions at depths.

Mechanisms for moving plates suggested by some scientists: Drag, pull, slide and push.



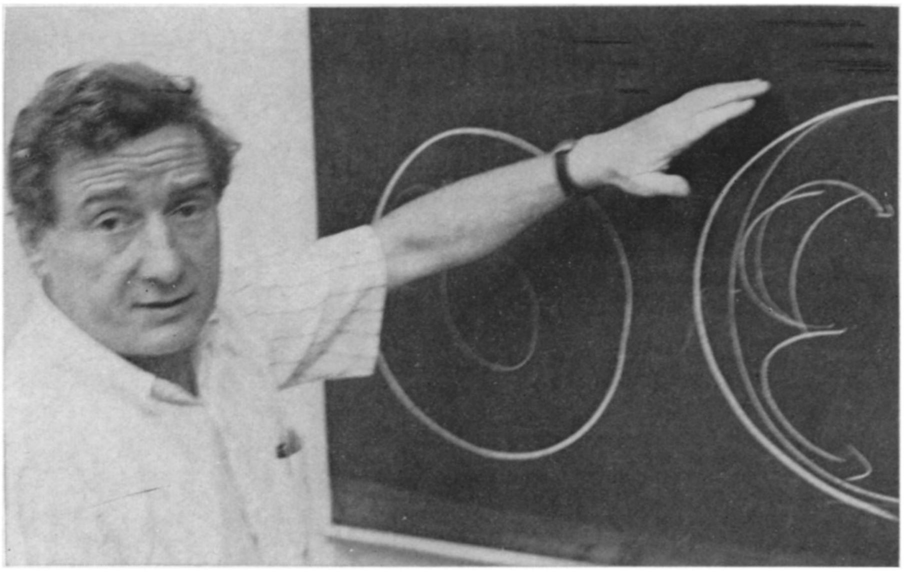
Robert Trotter/L. Lliboutry

Most of the proposed explanations for the plate motions rely on some form of convection in the mantle. Convection is of course merely the transfer of material and heat in a fluid medium in response to density differences. The simplest example is water boiling in a kettle. Heated water tends to rise and supplant the cooler, more dense water above. The process is common in the natural world. Convection currents in the liquid metal core generate the earth's magnetic field. Convection currents in the atmosphere produce vigorous thunderstorms.

The source of heat to initiate and maintain thermal convection in the earth is generally considered to be the continuing radioactive decay of isotopes of uranium, potassium and thorium. The original heat energy of the earth—if indeed the earth had a hot origin—need play little or no role. Some contribution to convective motion—the relative amount is debated—probably also comes from chemical differentiation of materials within the earth.

The mantle is solid, and this for a long time posed a difficulty to the convection idea. But now it is known that under suitable conditions of temperature and pressure solids can remain rigid in respect to fast-acting forces such as earthquake waves but undergo plastic deformation and flow in response to slow but persistent forces.

"Thermal convection of some sort or another is the only thing I can see that can do it," says Dr. D. P. McKenzie of Cambridge University. "There isn't much disagreement about that. Most of the disagreement is that people



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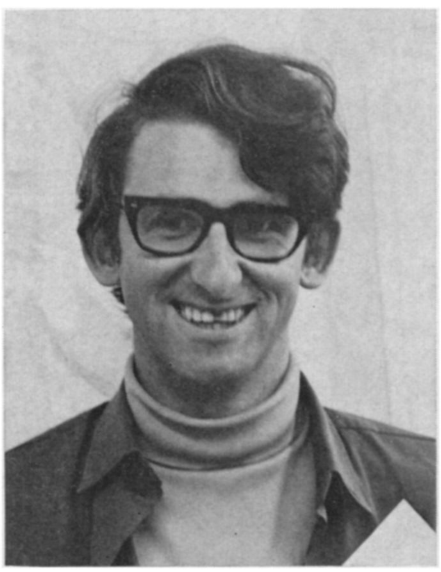
Runcorn (above) and McKenzie: Some form of convection in the mantle.



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are trying to explain the convection in ways that are too simple."

The old idea of giant convection cells, envisioning a rising flow of mantle material beneath the ocean ridges, a descending flow beneath the ocean trenches, and a return flow, closing the cycle at some layer deep within the mantle, he and many others regard as far too simplified a picture.

"I avoid the term 'convective cells' as much as people in the Middle Ages avoided the term 'devil,'" says Dr. Walter M. Elsasser of the University of Maryland. "All one can say is that material goes down some place and comes up another place."

The point is that when one has said that convection is in some way related to the motions of plates over the surface of the earth—and not all earth scientists even agree with that—one still has not said much. There are many different forms the convection could take; the motions and features of the earth's surface, in the view of most, give no clear indication of what the underlying flow is like.

"Nobody knows a damn about the patterns underneath," says Dr. McKenzie. "Are they cells? We don't know. Where do they come up? We don't know. Where do they go down? We don't know."

An example is an ice flow floating down a river. It does go downstream and it can turn, but it does not mirror any of the complex, detailed motions going on underneath.

At the recent international symposium on the mantle in Flagstaff, Ariz., (SN: 7/11, p. 29), Prof. Louis Lliboutry of the University of Grenoble in France, in a summary presentation, drew on a blackboard schematics of four possible ways in which forces could be exerted on lithospheric plates. All four have been proposed at various times to try to account for the plate motions.

The first was carried plates. This was the earliest view, that the plates are carried along by frictional coupling to a shallow mantle layer moving horizontally in the same direction, like a conveyor belt transporting material from one point to another. The second was a pulling force on the leading edge of the plates by the weight of the descending slabs. Another was a self-sliding mechanism, in which the plate in effect slides downhill from the high mid-ocean ridges toward lower areas around the edges of the ocean basins. The fourth was a pushing mechanism, in which mantle material welling up at the mid-ocean ridges pushes the plates from behind.

As is often the case in science when a selection of ideas is advanced to explain some poorly understood phenomenon, there are objections to all four of the proposed models.

Dr. S. K. Runcorn, for instance, the University of Newcastle upon Tyne geophysicist who turned up some of the earliest paleomagnetic evidence from the continents for continental drift, expresses strong opposition to the suggestion that inherent properties of plates, such as the gravity-sliding idea, can account for the plate movements.

He believes that convection currents can explain the motions. Calculations he has performed show that convection currents in the mantle would be just strong enough to break apart plates at what then become mid-ocean ridges. Some geophysicists disagree with him, however. Lack of a satisfactory explanation for a force sufficient to break the plates and thus allow the whole motion process to start has been one big hang-up of some convection ideas.

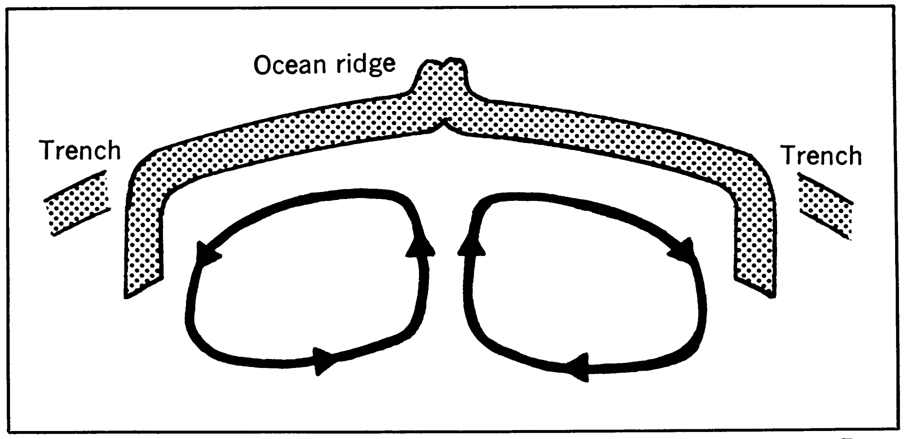
One of the proponents of the suggestion that gravitational pull on the leading edge of a plate may contribute to its motion is Dr. Peter Molnar of the Lamont-Doherty Geological Observatory. He believes it is premature to discard the idea. His view is that there is no need to invoke the more complicated ideas of convection until the simpler pull-hypothesis has been disproved. It would be logical to assume that a downward pull might begin on the leading edge of the plate, he reasons, because there the plate is older, therefore cooler, therefore denser.

Dr. Lynn Sykes of Lamont-Doherty points out that conditions for the gravity-sliding mechanism might exist in the southwest Pacific Ocean. There the crustal plate seems to slope generally downhill all the way from the East Pacific Rise westward to the Marianas. But according to him there are few if any examples for the fourth model, of a pushing force.

The prevailing sentiment, however, seems to be for the view of Dr. McKenzie, who says, "I think all four of Dr. Lliboutry's models are operative." The implication is that conditions are considerably different in different parts of the world and at different times, and no single model of plate motion is sufficient.

This may not be satisfactory to those who like their science neat and tidy. But answers seldom can be tied up in neat packages.

In an effort to bring some order to the situation, Dr. Donald L. Turcotte of Cornell University suggests that it would be convenient if everyone could at least agree that the driving mechanism in some generalized sense is thermal convection. If not, he says, someone should come up with an alternative. Historically, the hypothesized alternatives to convection have been either expansion or contraction of the earth. But few modern scientists would put themselves far enough out on a limb to suggest seriously that the earth



Robert Trotter

The idea of complete, giant convection cells is frowned on as too simple.

is getting larger or smaller.

Dr. Orowan, an emeritus professor of mechanical engineering at MIT, has proposed an alternative to convection—apart from the gravity-pull and sliding ideas. He calls it global transvection. It involves local heating in one region of the earth—either by radioactivity or possibly some large meteorite impact. The resulting expansion would cause a prolonged flow of the fluid, upper part of the mantle toward the cooler, opposite side of the earth. The cycle would be completed by a gradual rigid-body shift of the firm, deeper mantle in the opposite direction. His proposal, however, seems so far to have found few supporters.

What, then, is one to make of this confusing picture? Is there hope for gaining a better understanding of the driving forces in the mantle responsible for plate motions? Many earth scientists believe the answer lies with laboratory studies and sophisticated theoretical simulations of convection in media with the highly variable viscosity found in the mantle.

"I just don't see any way out except by using large computers," says Dr. McKenzie. "Only numerical methods can cope."

Dr. Turcotte and a colleague of his in Cornell's Graduate School of Aerospace Engineering, Dr. Kenneth E. Torrance, have been conducting some numerical analyses of convection. They use a model representing a vertical section of the earth 1,000 kilometers wide and 700 kilometers deep, with hypothetical temperatures of 1,150 degrees C. at the top of the mantle's soft layer and 1,830 degrees C. at the bottom. The velocity, temperature and pressure profiles they have obtained so far, they say, indicate the technique is feasible for studying mantle convection. They are limited, though, by both the cost of computer time and the capacity of existing computers.

The computer time required increases exponentially with the temperature difference between the upper and lower layer of their model. Using the temperatures of their present model, the Cornell scientists need 30 minutes of computer time to carry out the computations. "If we decreased the upper temperature to 1,000 degrees C.," says Dr. Turcotte, "it would take three hours on our computer. If we decreased it to 900 degrees, it would take a week. If we decreased it to 800 degrees, it would take several years."

Cornell

Turcotte: Hope in numerical studies.

With these kinds of problems they have not been able to add the descending part of the plate to their model, or to even begin studying three-dimensional instead of just two-dimensional flow. That will have to wait for much higher-speed computers.

Still, there is optimism for the future. Earth scientists are hopeful that the forthcoming international geodynamics program being planned by the new Inter-union Commission on Geodynamics (SN: 7/4, p. 9) will stimulate the laboratory and theoretical research needed to understand the deep-seated forces responsible for shaping the earth's surface. □