Plate Tectonics: The Geophysics of the Earth's Surface

A major conceptual revolution has been taking place in the earth sciences during the last 5 years. The central idea of the new theory—that the earth's surface consists of a small number of rigid plates in motion relative to each other—has gained increasing acceptance among geophysicists and geologists as a result of marine magnetic and seismic studies. Plate tectonics, as the theory is called, includes earlier notions of continental drift and sea-floor spreading as consequences of the relative plate motions which involve velocities as high as 10 centimeters per year. Plate motions and interactions are thought to be responsible for the present positions of the continents, for the formation of many of the world's mountain ranges, and for essentially all major earthquakes. But the forces that cause the plates to move are not yet understood; a lack of information about the earth's mantle, where the driving mechanisms are believed to originate, is a key difficulty.

Plate tectonic theory has simplified and unified widely separated fields in the earth sciences, from volcanology and seismology to sedimentary geology. In the process, many older ideas—that all marine sediments found on continents must have been deposited in shallow water, or that mountains were formed in place by lifting and folding of preexisting continental material—have been substantially modified. The way in which most geologists and geophysicists now view the evolution of the earth's surface differs so greatly from earlier ideas, that, as one scientist pointed out, existing textbooks in these subjects will have to be rewritten.

That continents drift had been proposed early in this century, but the idea was not widely accepted. The concept of large crustal movements was kept alive, however, especially by geologists in the Southern Hemisphere who were impressed by similarities in the rock formations and fossil remains of Africa and South America. In the 1950's, paleomagnetic work on the location of the ancient magnetic poles reawakened interest in the possibility of continental drift. Exploration of the ocean floor suggested that it is relatively young, compared with the continents, and discovered the fracture zones associated with the mid-ocean ridges. In the early 1960's, sea-floor spreading was proposed as a mechanism for continental drift. Supporting evidence was obtained from the pattern of magnetic anomalies that form symmetric stripes on either side of the ridges and from the seismic records of earthquakes whose epicenters were located along the ridge fracture zones. By 1967, there was strong evidence that oceanic crust was being created at the mid-ocean ridges. Data recorded from the deep earthquakes associated with the oceanic trenches indicated that the corollary process of crustal destruction was occurring as slabs of crust were shoved down into the mantle. Shortly thereafter, the theory that the earth's surface and its motions could be understood in terms of rigid plates was explicitly formulated.

Plate Theory

The theory of plate tectonics has now been extensively developed. The plates—as few as six plates in some models and as many as 20 plates in others are postulated to constitute all of the earth's surface—are believed to be 50 to 100 kilometers thick and to slide on the warmer, less rigid material of the upper mantle. The boundaries of the plates do not generally follow continental boundaries, so that plates often include both oceans and continents. Tectonic activity, according to the theory, is concentrated along plate boundaries, which are of three types: spreading centers, where new crust is created as two plates move away from each other, such as at a mid-ocean ridge; subduction zones or trenches where one plate is thrust under another as they move toward each other; and faults where two plates slide past each other. Plate models have been developed and used by Jason Morgan of Princeton University, X. Le Pichon of the Centre Océanologique de Bretagne in France, and others, in their reconstructions of past crustal motions (*1*).

A survey of worldwide seismic data by Bryan Isacks, Jack Oliver, and Lynn Sykes of Lamont-Doherty Geological Observatory in New York provides additional evidence in support of the plate concept (*2*). The study shows that most earthquakes are confined to narrow belts (the plate boundaries) surrounding large areas where earthquakes are infrequent; the directions of motion of the plates, as determined from the seismic data, are in good agreement with plate tectonic models and with magnetic evidence from the sea floor. The agreement between theory and two independent types of evidence is to many earth scientists convincing proof of the plate tectonic concept, at least in its broad outline.

Geophysicists are now focusing a great deal of research on the driving motions of the plates and the details of plate movements. In the latter process, refined models of the earth's surface are constructed using data from the worldwide mapping of magnetic anomalies on the sea floor and from the detailed analysis of earthquakes in the trenches. Walter Pittman and Manik Talwani of Lamont, for example, have used magnetic data to reconstruct the evolution of the Atlantic ocean, which apparently opened in several stages. The central Atlantic, for example, seems to have opened before the south Atlantic, and the motion of the American plate relative to Europe has been in a different direction from that relative to Africa. The relative motions of Europe and Africa have consequently been very complex. The Lamont geophysicists have inferred this motion by working out the motion of each continent individually with respect to the mid-Atlantic spreading center.

Some progress has also been made in the understanding of how plates evolve. Plates are continuously being created at the ocean ridges and destroyed in the trenches, and, as plates interact, new trenches or ridges may open up. In several locations three plates come together in what is known as a triple junction; Dan McKenzie of Cambridge University and Morgan have shown that the orientation of plate boundaries at such a point determines whether or not such junctions retain their geometry as the plates move. The migration of triple junctions, they find, is associated with many changes in plate geometry which otherwise would appear to have been caused by a change in the direction of relative motion between two plates. In the north Pacific, for example, triple junctions appear to have played a major role in the complicated geological history of the west coast of North America and the surrounding sea floor.

Although the geometry of the plates and the kinematics of their motions are now reasonably well known, the mechanisms that drive their motion, and in particular the nature of the driving forces, are not understood. Several conflicting models have been proposed to explain plate motion; most models are based on the assumption that some form of thermal convection within the mantle is responsible. But whether the convection is restricted to the upper few hundred kilometers of the mantle, or whether it also involves the lower mantle, is actively debated.

The uncertainty concerning the driving mechanism reflects present ignorance about the composition and properties of the mantle itself, for which very little quantitative evidence is available. Early estimates of the viscosity of the lower mantle (below 700 km), for example, had indicated that it was too high to allow convection. But the evidence for such a viscous mantle seems inconclusive, and attempts have been made to calculate the rheological properties of the mantle directly with the use of models derived from solid state physics.

Here again, however, there are conflicting theoretical results. Some models of mantle composition assume that its response to stress involves creep by means of mass diffusion of atoms, such as proposed by R. Gordon of Yale. Such models predict a high viscosity for the lower mantle. In contrast, J. Weertman of Northwestern University believes that creep proceeds according to a nonlinear law by means of a dislocation motion at high stresses; his calculations predict a substantially lower viscosity that would permit deep convection (*3*). The application of either model to the geophysical situation is complicated because the composition of the mantle is not well known. Laboratory experiments that simulate mantle conditions may provide information that will help distinguish between the two theories.

Because of gaps in the data on the mantle, it is hard to do more than show that a given model of the driving mechanism is consistent with observations; predictions are difficult to check. It is known, for example, that the heat flux from the earth is unusually high at the mid-ocean ridges. McKenzie estimates that the anomalous heat flux can be explained by the upwelling of molten mantle to fill the gap made as two plates pull apart. Hence, he believes, the heat flux data provide no information about the earth's interior that could be used to distinguish between competing models. Seismic studies have also provided evidence of inhomogeneities in the mantle, but very few undisputed facts have emerged.

Driving Mechanisms

Whatever the driving mechanism, an enormous amount of energy—at least 10^{26} ergs per year, according to Leon Knopoff of the University of California at Los Angeles—is needed to move the huge plates. Many geophysicists believe that the source of energy is the heat released by the radioactive decay of uranium, thorium, and potassium that occur in the mantle in trace amounts. Others think that energy released in changes of phase associated with formation of the core, tidal forces from the moon, or gravitational forces are also involved.

Thermal convection can occur in a fluid heated from below, and over long periods of time the mantle can apparently behave like a fluid. One type of theoretical model for plate motion is based on convection cells similar to those studied by Lord Rayleigh. According to model calculations by Don Turcotte and Ken Torrance of Cornell University, the drag of the moving fluid on the bottom of the surface plates could cause their motion. The numerical calculations include the effects of temperature-dependent viscosities on the flow pattern. The heat flux at the earth's surface that is predicted by these simplified models agrees approximately with the observed flux.

Seismic data and laboratory experiments on the properties of matter at high temperature and pressure indicate that the mantle material undergoes at least one phase change at a mean depth of 400 km, resulting in a density change of about 7 percent. Some geophysicists have assumed that this phase change would bar any flow across it and hence that only shallow convection could occur. Recent calculations by Turcotte and by Gerald Shubert of UCLA, however, indicate that the phase change may have a destabilizing effect and thereby increase the convection, which according to their model would involve material in the mantle down at least to 700 km (*4*).

A second type of mechanism to explain the movement of the plates depends on the assumption that the weight of the relatively cold surface plate descending (in a trench) into the warmer and less dense material of the mantle would help to pull along behind the portion of the plate still on the earth's surface. Calculations by McKenzie have indicated that the mechanism is feasible and could play an important role in determining plate motion, although it might be only an auxiliary driving force. Bryan Isacks and Peter Molnar of Lamont have analyzed earthquakes in the trenches, and their results give some support to the idea that the descending plate is pulling its surface portion behind it.

A third type of mechanism is based on the assumption that the convection is occurring deep within the lower mantle. Morgan, for example, has suggested that plates are driven by a small number of hot spots that represent convection plumes rising from the lower mantle. The rising material in this model spreads out in the upper mantle to provide the stresses on plate bottoms; the return flow is accomplished by a gradual settling throughout the mantle. The resulting flow pattern for deep convection, Morgan believes, is thus more analogous to that of a cumulus cloud than to the roll or cell-like pattern visualized for shallow convection. The hot spots in Morgan's model are assumed to be fixed with respect to the mantle and are located near present-day sites of volcanism, such as Hawaii and Iceland. Apparent differences in the types of basalts found in the mid-ocean ridges and oceanic islands are explained by this model as the result of island chain formation by the motion of a plate across a fixed hot spot. The ages of the Hawaiian Islands, for example, increase toward the northwest, and the present active volcano is at the southeast end of the chain. Morgan calculates that the orientation of this and other island chains is consistent with past motions of the Pacific plate.

Despite present uncertainties about the driving forces, the plate concept has had a remarkable unifying effect on the earth sciences, and has stimulated renewed activity in continental as well as marine geology. A second article will describe recent geological studies of mountain building and formation of continents.—ALLEN L. HAMMOND

References

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