Plate Tectonics: What Forces Drive the Plates?

The widely accepted theory of plate tectonics says that the appearance of the surface of the earth results from the movement of more than a dozen thin crustal sheets, or plates, although no one knows what makes the plates move. For some years, after the theory's proposal in the 1960's the best guess was that convection cells in the mantle under the plates dragged them across the earth's surface. Confirmation by observation or theoretical study proved difficult. Some researchers have taken a new tack by deducing possible driving forces from observed plate motions. They and others now believe that the mantle need not be an active participant in plate motion. Rather, thermally induced properties of the plates themselves, such as density and elevation variations, may be responsible for their movement. Although perhaps as much as half of those in the field lean toward this view, no one contends that the matter has been proved one way or the other. The supporting geophysical evidence remains too equivocal.

The study of mantle convection and its possible role as a plate driving force has had a long and somewhat frustrating history. Even before the theory of plate tectonics, mantle convection was suspected to occur on a purely theoretical basis but was not confirmed by observation. The discovery that plates form from upwelling magma at ridge crests and eventually sink into the mantle at ocean trenches demonstrated once and for all that some sort of convection occurs within the earth, but this discovery also revealed considerable obstacles to its observation. Geologists, who had hoped to see the effects of mantle convection on surface features, like the scum on a boiling liquid, found instead that it was difficult if not impossible to detect convection patterns masked by up to 100 kilometers of relatively cold, rigid plate.

When theoreticians again approached the problem of mantle convection, once the general scheme of plate tectonics had been worked out, they still had to contend with a considerable dearth of information. No one had seriously studied the deformation and flow of any material under mantle conditions. In addition, the properties of mantle rock are expected to change abruptly under varying temperature and pressure because of changes in crystal structure.

Two approaches are now being taken in studying mantle convection and its interaction with the plates, but they are only grudgingly yielding insight into mantle processes. For example, D. P. McKenzie of Cambridge University and Donald Turcotte of Cornell University, among others, have developed numerical models which predict the behavior of fluids under mantle conditions on the basis of initial conditions and the laws of fluid motion. These models describe the resulting motions in a way that can be compared with other models as well as with actual geophysical observations. A major drawback at this time, McKenzie says, is the difficulty of extending such models from two dimensions to three.

Frank Richter of the University of Chicago has constructed physical models in the laboratory to duplicate convective conditions thought to occur in the mantle. While laboratory models produce convection in three dimensions, they do not yield the desired variety of descriptive details to validate the results fully by comparison with geophysical data, according to McKenzie. In addition, Richter points out, laboratory models have not yet shown how convection cell patterns could be responsible for some plate characteristics, such as their large and variable sizes. Both methods are hampered by the lack of knowledge of the physical conditions, such as viscosity, prevailing in the mantle.

Some researchers have attempted to avoid these difficulties by ignoring the details of mantle behavior and using the better understood behavior of the rigid plates to infer the forces that may be acting on them. Such numerical modeling experiments were independently and simultaneously carried out by two groups: Donald Forsyth, now at Brown University, and Seiya Uyeda of Tokyo University, and a second group consisting of William Chapple and Terry Tullis, both of Brown University. Both groups concluded that active mantle convection is not necessary to drive the plates and that their movement can be reasonably explained by the pull of the cooler, dense edges of the plates as they sink into the upper mantle.

The procedures adopted by the two groups were essentially the same. Their basic assumption was that the plates are not being accelerated, so that the sum of the forces acting on the plates would be zero. The problem thus becomes a matter of finding a geophysically reasonable combination of forces that minimizes the net force acting on the plates.

First, both groups decided what forces might in any way be affecting the motion of the plates. These forces, eight or more in all, included the sinking of plate edges, or slabs, into trenches (slab pull), the sliding of the plates off the topographically higher ridges (ridge push), and a force acting on the bottom of the plates (mantle drag force), which could be either a driving force or a resistive force.

Then, assumptions were made about how each force was expected to behave. These assumptions were based on geophysical observations, but they sometimes differed in the two studies.

The next step was to specify the observed shape and velocity of each of the 12 plates used in the studies. The only unspecified factors in the system, the relative sizes of the eight forces, were then calculated by a computer.

The two groups agree that a reasonable balance of forces can be achieved with a very large slab pull relative to other possible driving forces. But resistance to the slab's descent into the trench is also large. The resulting force, they claim, is still a significant net pull on the plate and is the primary factor determining the motion of the plates. The coupling between the plate and the mantle works out as a small resistive drag, larger under the thicker continental portions of plates than under the oceanic portions. Richter has reached the same general conclusions on the basis of a different theoretical model that includes both the rigid plate and the mantle below it.

Critics of the plate modeling approach suggest that the outcome of any model is too dependent on its assumptions to place complete faith in the results. Forsyth argues that minor plate forces, which he believes are not actually resolved in these models, are indeed sensitive to specific assumptions about the forces, but that the conclusions about the major forces are not. Chapple and Tullis contend that the general agreement of the two studies, in spite of some differences in the formulation of forces, lends support to the credibility of the method.

Some critics see this insensitivity to differences between models as indicating that the earth's major plates do not differ enough from each other for the purpose of model building. Forsyth observes that, in theory, the 12 plates used should be sufficient to completely define the

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eight forces, but he concedes that some, such as the Cocos, Nazca, and the Pacific plates, are rather similar. They vary widely in size but little in velocity. Attempts have been made by several groups to get around this problem, with little success so far, by also employing shapes and velocities inferred from the geologic record of plates believed to have existed in the past.

A number of present-day plates have been cited as behaving contrary to the general predictions of the plate models, but the increasingly detailed picture of observed plate movements is making this

Speaking of Science

The Media: The Image of the Scientist Is Bad

Science and scientists, many observers argue, have been taking a beating in the media. The press, the movies, and, especially, television convey the image that scientific progress is hazardous and that scientists are frequently foolish, inept, or even villainous. This portrayal, critics contend, is eroding public support for science and may be turning away many potential Einsteins, Paulings, and Pasteurs before they mature enough to appreciate the joys and wonder of science. This concern has been the focus of several magazine articles and a symposium at the recent annual AAAS meeting. Some examples:

Science gets "a lousy press," science fiction author and *Analog* editor Ben Bova told the AAAS symposium. "A Russian satellite falls on Canada and scientists get clobbered." The movies are even worse, he adds; in them, "scientists are portrayed as having moral sensitivities no higher than a Hollywood producer's."

Many of the scientists portrayed in Saturday morning cartoon shows, Carl Sagan wrote in a recent issue of *TV Guide*, are "moral cripples driven by a lust for power or gifted with a spectacular insensitivity for the feelings of others—and the message conveyed to the moppet audience is that science is dangerous."

The reasons for this portrayal are many. One of the most important, Bova says, is that "people fear science because it makes changes." While the law, education, and other fields of endeavor look backward for precedents and justification, science looks to the future and tries to establish new precedents. That change, he argues, is frightening. The misperception conveyed by the media is possible, he adds, because most Americans have never met a scientist. "The closest they ever come is a high school science teacher, and maybe that's why scientists have such a bad image."

Equally important is the nature of the media and the people who work in it. Science fiction—the predominant form in which science is displayed in movies and television—is primarily a drama of ideas, television script editor and science fiction author David Gerrold told the AAAS meeting, and "Ideas, in and of themselves, do not photograph well." Most science fiction stories in movies and on television thus are westerns, soap operas, and other conventional plot forms to which science fiction trappings have been added almost as an afterthought. Scriptwriters, furthermore, seem to have a uniform lack of scientific background. "The primary qualification for success as a television scriptwriter," he says, "is the ability to turn out 56 pages of typewritten dialogue in 10 days." Producers and directors also "suffer from an impoverished world view; they do not even have an idea of Newton's three laws of motion," which is why we have such spectacular—albeit nonsensical—dogfights in space in the movie *Star Wars*. It is thus not suprising that there are so many inaccuracies and errors in science fiction dramas, errors that give the lay public a warped sense of science.

Gerrold cited one science fiction script submitted to him (and mercifully rejected) which "began by telling us that all life on earth was in dire peril because there was about to be an eclipse of the galaxy. . . ." An infamous example cited frequently is the use of "parsecs" as a unit of speed in *Star Wars*. Isaac Asimov cataloged other blunders in another recent article in *TV Guide*. One example from the Saturday morning series *Space Academy* had two space ships passing through a black hole and later returning. Similar situations have occured in the British import *Space 1999* and the new series *Quark*. It would seem, Asimov says, "that the hard-working, but uneducated, people behind the shows think that a black hole is a gap among the stars, or perhaps a space whirlpool, through which one can scoot and return."

Scientific advisers are rarely used on such shows, Gerrold says, perhaps because the creators themselves share the attitudes being purveyed. Scientists are also frequently unable to adapt to the needs of the shows. Gerrold cited the live-action series *Land of the Lost*, in which a father, son, and daughter on a camping trip are swept into a prehistoric land populated by dinosaurs and cavemen. An anthropologist was called in to create a realistic language for the cavemen. The anthropologist decided that the new "Pakuni" language, for scientific reasons, should have no "l" or "h" sounds. Unfortunately, Gerrold says, the lead characters in the series were named Will, Holly, and Marshall. The cavemen's dialogue, furthermore, translated into long speeches that were virtually unpronounceable by the actors. The anthropologist refused to modify the language, Gerrold says, and the eventual result was that the cavemen's speeches deteriorated into an inarticulate series of grunts.

What can be done to improve the situation? The most likely solution, both the panel and the audience at the AAAS symposium agreed, appears to be for individuals and organizations such as AAAS to protest to movie studios and networks when inaccuracies appear and when scientists are portrayed in a denigrating fashion. "When people tell a network, 'This is wrong,' " Gerrold says, "they appoint a vice-president to listen to you. They don't want anybody to make waves. All they want is to see the money keep rolling in."

This technique has been used successfully by minority organizations of blacks, chicanos, women, and gays—to the point where scripts portraying members of such minorities are submitted to the groups to ensure that they do not present stereotypes. Scientists are more of a minority than any of these groups, Gerrold adds, and with enough pressure, could create a similar situation for themselves.

—THOMAS H. MAUGH II

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a more complicated argument than it once seemed. Examples of apparent problem behavior are the African plate, which is not bounded by any subduction zones, but still moves and even contains a new spreading center, and the Antarctic plate, which is entirely surrounded by ridges but has been thought to move.

Forsyth cautions that the models were not intended to explain every detail of plate motion, pointing out that they involve simplifications and that forces other than slab pull may be important in special circumstances. He also observes that the models cannot say anything about how plate motion began.

Since plate motions were an initial input to the model, most plate behavior must conform to the model. If some plates did not, other major forces might be implied. The results of a recent refinement of plate motion measurements by Bernard Minster of the California Institute of Technology and Thomas Jordan of Scripps Institution of Oceanography illustrate general agreement between rigid plate models and the complexities of observed plate motion. Minster notes that measurements of slow plates are still rather imprecise, but their best estimates indicate, for example, that the African plate, comprising the African continent and the surrounding ocean floor, slowly rotates counterclockwise about a point within the plate itself (about 400 kilometers off the coast of western Africa). The fastest portion of the plate is moving only 1 to 2 centimeters per year compared to 8 centimeters or more per year for some plates. These speeds were calculated relative to a framework of "hotspots," such as the one beneath the active volcanoes of Hawaii. Hotspots appear to move very slowly, if at all, relative to one another. With respect to this reference, movement of the Antarctic plate is not detectable within the error of the determination, according to Minster. These findings seem to suggest that, when significant subduction is absent, plate movement is likely to be slow and complex. The modelers find these results to be compatible with theirs.

Minster and Jordan and others have also found that oceanic plates having no continental portions move faster than plates having significant areas of continental crust. He finds that oceanic plates move about 8 centimeters per year on the average while the movement of continental plates averages only about 2 centimeters per year. Proponents of the slab pull theory believe that this is evidence of increased drag beneath the thicker continents, as is indicated by the plate models.

Concern continues among some geophysicists that these plate models are incomplete and do not represent all possible mechanisms for plate motions. Geoffrey Davies of the University of Rochester has constructed a plate model in which the mantle must provide a strong driving force rather than a small resistance. While he does not claim that his model is strong evidence for mantle convection driving plate motion, Davies does believe that it demonstrates the nonuniqueness of plate model solutions.

There are some basic differences between Davies' model and the slab pull models of Forsyth and Uyeda and Chapple and Tullis. Davies' model resulted from his concern that the assumptions of the previous models about plate-mantle interaction, while being reasonable, are not the only geophysically plausible ones. His model contains no initial assumptions whatsoever about the behavior of the mantle drag force, but it does specify the size of the likely forces operating at the margins of the plates. Davies explicitly assumes a relatively high frictional stress level of 1 kilobar (1 bar is one atmosphere of pressure) at the zones where two plates slide by one another, such as along the San Andreas fault. Such a large resistance requires a large net driving force to overcome it, which can only be supplied by the mantle drag force.

Stress Levels

The existence of relatively high stresses in the crust was most recently suggested by Thomas Hanks of the U.S. Geological Survey (USGS) at Menlo Park. He believes that the high mechanical strength of crustal rock, as demonstrated by laboratory tests of their breaking strength, may allow equally high stresses in the crust. Hanks points out that the actual stresses at plate margins are not known within an order of magnitude. Thus, he concludes, the forces driving the plates cannot be even guessed at. Those favoring low stress levels, on the order of a few hundred bars, accommodate the laboratory results by assuming that conditions within the earth lower the effective strength of crustal rocks, preventing the buildup of high stress.

The slab pull models suggest low stress in the crust, but critics often maintain that low stress is inherent in the assumption of the models. Forsyth does concede that low stresses are implied in that surface features, such as ridges, trenches, and faults, were assumed to reflect the activity of the driving forces. If mantle drag were indeed the driving force, these features could not be used to construct a model. But, Forsyth says, such mantle activity cannot be assessed directly in the manner that a plate model can. Thus, he believes that plate modeling is the more productive approach at this time although it implies low stress.

Observational evidence supporting low stress in the plates includes the apparent lack of frictional heating along fault zones and the low levels of stress released by earthquakes. Frictional heating along a fault should appear at the surface as a heat flow anomaly. Neither James Brune of the University of California, San Diego, nor Arthur Lachenbruch of the USGS, Menlo Park, found any anomalies on the San Andreas fault in the areas that they surveyed. Hanks suggests that, among other possibilities, the lack of an anomaly may be due to the dispersion of frictional heat by migrating groundwater; but Brune believes that such a scheme involves some very unlikely behavior on the part of the warmed groundwater.

The evidence from studies of stress released during earthquakes is circumstantial, as it involves the debatable question of whether the observed stress release of the largest earthquakes represents the total stress in the plates. Randall Richardson and Sean Solomon of the Massachusetts Institute of Technology think that it does. They have analyzed the seismic signals generated by the infrequent earthquakes in the middle of plates and have concluded that the total drop in stress is no more than a few hundred bars. This is the same amount of stress that they would expect to be produced by push from the weight of the plate sliding off the elevated ridge. The coincidence, they believe, suggests that nearly total release occurs. A stress of a few hundred bars was also calculated by Forsyth and Uyeda using the elevation of the ridges as a known force for the calibration of all the forces.

Another type of earthquake-derived data, the type of stress in the plates, is interpreted as indicating that slab pull is probably not the only force affecting the plates. Lynn Sykes and Marc Sbar of Lamont-Doherty Geological Observatory have deduced from studies of earthquakes within oceanic plates that the areas away from the ridges are under compressional stress. They believe that plates are compressed even near some trenches. This runs counter to the expectation that tensional stress would predominate if slab pull were the only significant force acting on the plate.

Richardson and Solomon have proposed that the observed compressional stress in the crust is most consistent with

(Continued on page 90)

RESEARCH NEWS

(Continued from page 38)

a small resistive mantle drag force and a ridge push that is about the same size as the net pull from trenches. They reached these conclusions by constructing a mathematical model relating plate driving forces to plate stress. In much the same way that the combination of plate forces had been adjusted to fit observed plate motion in other models, they adjusted the relative sizes of the forces until the stress distribution generated by the model most closely resembled that observed.

Although the presence of compressional stress in the plates is often cited as evidence against the importance of slab pull, Forsyth and Uyeda believe that their model is generally consistent with current stress data. This is possible, they say, because the net pull from the trenches is small. Although ridge push is small and is counteracted by a number of smaller opposing resistances in the system, it is still able to compress the plates, they say.

The situation may be more complicated than even these multiple force models indicate. Turcotte has suggested several other possible sources of stress in addition to the forces driving the plates. He believes that these stresses may be induced by the cooling of newly created plates, the nonspherical shape of the earth, or changes in the weight of plates because of erosion and sedimentation.

Additional kinds of geophysical evidence bearing on the question of what drives the plates may be accessible to current survey techniques. Patterns of mantle convection should depend on how the mantle interacts with the plates above it. Such patterns may be detectable as patterns of gravity, heat flow, and crustal elevation variations over oceanic plates. Combining the latter two types of data, Kevin Furlong and David Chapman of the University of Utah have found what they consider to be a strong suggestion of long, longitudinal convection cells in the central and eastern Pacific. Chapman points out that, although their interpretation is debatable, he believes that it tends to argue against the plates being driven by the mantle.

Current data are obviously not decisive, but they are expected to improve in quantity and quality. Modeling of historical plate behavior, refinement of global geophysical surveys, and extension of plate stress measurements will continue, but, as Forsyth puts it, "No one is willing at this time to stake a reputation on what drives the plates."

—RICHARD A. KERR

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(Continued from page 43)

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Hydraulic Behaviour of Estuaries. D. M. McDowell and B. A. O'Connor. Halsted (Wiley), New York, 1977. viii, 292 pp., illus. $27.50.

Image Formation and Cognition. Mardi Jon Horowitz. Appleton-Century-Crofts, New York, ed. 2, 1978. xviii, 398 pp., illus. $18.95.

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Introduction to the Mathematics of Inversion in Remote Sensing and Indirect Measurements. S. Twomey. Elsevier, New York, 1977. x, 244 pp., illus. $65. Developments in Geomathematics 3.

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Paradox. The Case for the Extraterrestrial Origin of Man. John Philip Cohane. Crown, New York, 1977. x, 182 pp., illus. $10.

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Perspectives on Social Psychology. Clyde Hendrick, Ed. Erlbaum, Hillsdale, N.J., 1977 (distributor, Halsted [Wiley], New York). vi, 362 pp., illus. $19.95.

Rocketship. An Incredible Voyage through Science Fiction and Science Fact. Robert Malone with J. C. Suarès. William E. Maloney, Ed. Harper and Row, New York, 1977. 128 pp., illus. Paper, $6.95.

Scleractinia of Eastern Australia. Part I, Families Thammasteriidae, Astrocoeniidae, Pocilloporidae. J. E. N. Veron and Michel Pichon. Australian Institute of Marine Science, Townsville, Queensland, 1976. vi, 86 pp., illus. + plates. Paper, A$4.70. Australian Institute of Marine Science Monograph Series, vol. 1.