Meetings

Petrologic Implications of Plate Tectonics

The constraints imposed by petrology on the current dynamic model of the earth were discussed at a symposium in honor of Dr. Caryl P. Haskins, retiring president of the Carnegie Institution of Washington. The symposium, sponsored by the Geophysical Laboratory, took place from 17 to 20 March 1971 and was attended by 31 field and experimental petrologists, seismologists, geophysicists, geochemists, and physicists, eight of whom were from abroad. The symposium consisted of one formal talk and five informal sessions.

The relation of plate motions to magma character was emphasized by James Gilluly (U.S. Geological Survey, Denver). He believes that collisions of plates at the boundaries between continents and oceans (for example, west coast of the United States) yield andesitic magmas palingenically derived from the subducted oceanic basalts and sediments. Gilluly thought that the differentiation of such magmas was in large part determined by the sedimentary processes operating on the oceanic crust. He noted that the volume of sediments off the west coast of the United States was only one-sixth that off the east coast. As a minimum, he calculated, some 1500 km of oceanic crust had been overridden as America moved westward. Collisions of two ocean plates at the boundaries (for example, Aleutian Islands) may also yield, by the partial melting of eugeosynclinal sediments, andesitic magmas with little or no sialic (continental) contamination. He was particularly interested in the way the East Pacific Rise was destroyed by the westward movement of America and was converted into the Aleutian trench early in the Tertiary. The collisions of two continent plates at boundaries (for example, Alps) yield little or no magmatism apparently because of the tight structural conditions. Gilluly suggested that the Insubric line in the Alps marks the subduction zone (that is, where one plate has slid beneath another) and that the Alps actually have a granitic basement. Of considerable concern to him were those magmas not related to subduction zones.

Mid-Ocean Ridge Environment

Discussion of the ridges, some 60,000 km long, yielded the largest number and variety of schematic models illustrating rock types and physical state. One of the more surprising suggestions as set forth by Dan P. MacKenzie (University of Cambridge, England) was that dynamics in the asthenosphere* was not necessarily the main key to understanding plate tectonics and that there was no persuasive evidence yet for convective upwelling at the ridge. The net driving force on the plates could not be related to simple convective cells in the asthenosphere. The increase in heat flow and elevation toward the median ocean ridge could be accounted for by magma filling the plate separation. The transfer of mass into the crack, according to E. R. Oxburgh (Oxford University, England), dominated the thermal regime. He also introduced the idea that magmas acted as "thermal buffers" and that knowledge of the pressures and temperatures of melting of rocks believed to exist at depth in the ridge environment would, therefore, be helpful in defining the thermal regime. Oxburgh believes that we must expect large lateral variations of temperature as well as those with depth. In fact, David James (Department of Terrestrial Magnetism, Carnegie Institution of Washington) raised the question of whether the present variation of geothermal gradient with geography might not be as great as the variation throughout geologic time.

Production of magma beneath the ridge may result from the (convective?) rise (from a high-temperature, high-pressure environment) of solid garnet peridotite, without loss of heat, into a lower pressure environment where melting can begin. Generation of the different types of magma appears to depend on several factors: (i) the composition of the parental material; (ii) the depth at which the magma is separated from the parent material; (iii) the degree of partial melting achieved; (iv) the physicochemical constraints that lead to repetitive magma types; (v) the water content, stored in hydrous phases; and (vi) the extent of fractionation en route to the surface.

The predominant rock found along the ridges is a low-potassium olivine tholeiite. Olivine or plagioclase is the first silicate phase to crystallize, almost to the exclusion of clinopyroxene. Pigeonite is rare and hypersthene is only occasionally found in these lavas, according to J. R. Cann (University of East Anglia, England). This is an important observation because hypersthene is considered a major phase in the parental material. It was suggested by A. Miyashiro (State University of New York, Albany) that the differentiation products could be derived by extraction of olivine or plagioclase. If so, this primary control must operate within 30 km of the surface where olivine and plagioclase are stable together.

P. W. Gast (National Aeronautics and Space Administration, Houston) described a particularly striking relationship in which the oceanic tholeiitic basalts had about the same proportions of rare earths as chondritic meteorites except for a slight deficiency in the lighter elements. In contrast the alkali basalts, occasionally produced at the ridge, were greatly enriched in the light rare earths. He categorized basalts by their content of rare earth element patterns and suggested that

* Three layers are distinguished below the surface of the earth. The *lithosphere* includes the crust and uppermost mantle to a depth of about 50 to 200 km and has significant strength. The plates are composed of lithosphere. The *asthenosphere* has effectively no strength in a geological time scale and extends from the base of the lithosphere to several hundred kilometers. It corresponds, more or less, to the low-velocity layer of seismology. The *mesosphere* extends below the asthenosphere to the lower portion of the mantle remaining, may have strength, and is relatively passive in the plate tectonics concept.

oceanic tholeiite may be the result of extensive melting of the parent material and that the alkali basalts represented a lesser degree of melting. He called attention to the unique partition of rare earths in the equivalent high-pressure phases and the effects their partial melting would have on the magmas produced.

A new kind of open fracture zone on the ridge—in contrast to the usually closed transform fault zone—was proposed by W. G. Melson (Smithsonian Institution, Washington, D.C.). Of particular importance are the nepheline-normative alkali basalts (those usually critically undersaturated) which issue. The need to consider the effects of structural control on the magmas produced in the ridge environment became evident.

There was general agreement that Iceland, although typical structurally, was indeed a petrologic anomaly on the ridge. The dike swarms, believed by Ian Gibson (Bedford College, England) to be the feeders of the Icelandic lavas, are arranged in belts suggesting localized activity. The increase in frequency of dikes with depth indicated that the region at the incredibly shallow depth of 5 km would consist only of dikes. Thus, dike swarms may be one of the clues to finding old mid-ocean ridges which have ceased to function. Silica-rich rocks in Iceland were described by H. S. Yoder, Jr. (Geophysical Laboratory, Washington, D.C.), as the initial magmatic product of a partial melting sequence of a quartz-normative parent which also yielded basalt. He emphasized the absence of intermediate rocks in his model of magma production—the paucity of intermediate rock types in Iceland has long been recognized and debated. Another anomalous area, the East Pacific Rise, was described by W. B. Bryan (Woods Hole Oceanographic Institution). It has no median valley, a thin crust, exceptionally high heat flow at the crest, and some rock types (on islands) such as peralkaline trachytes, commendites, and pantellerites, which are very rare in the deep-ocean environment.

Abyssal Plains and Their Islands

The oceanic crustal portions of the plates were also discussed but with considerably less vigor because of lack of data. Large new collections of rocks from a limited number of deep-ocean dredge hauls indicate a wide variety of fresh, weathered, and metamorphosed basalt, some very coarse-grained and layered gabbros, as well as serpentinites (confined to the Atlantic and Indian oceans), and a range of peridotites. Ocean bottoms *are* as complex as continents. A clever reconstruction by F. Aumento (Dalhousie University, Nova Scotia) of dredge-haul material from the Mid-Atlantic Ridge at 45°N yielded a layered sequence of pillow basalts overlying massive basalt sills, flows, and dikes, and then metamorphosed basalts progressively changing with depth from greenstone to amphibolite facies. The layers are studded with masses of serpentinite. The sequence is related by some to that formed in the so-called ophiolite suite of the continents, believed to be indicative of preexisting oceanic crust. There was considerable disagreement on this point mainly because of the diversity of opinion on the definition of ophiolite. The question was raised as to whether the basalt reached at the bottom of the deep-sea drill holes was sills or flows. The induration of the adjoining sediment was unfortunately not sufficiently diagnostic.

New and extensive petrologic data on the islands on the abyssal plains have become available. The Hawaiian chain was described by E. D. Jackson (U.S. Geological Survey, Menlo Park, Calif.) as having been generated by the passage of a plate over a relatively fixed hot spot or "plume." Thereby the chain, the locus of points of individual volcanoes, marks the trail of the plate. The concept of a single hot spot was challenged because of the magma depletion problem and the difficulty of reproducing the magmatic differentiation cycle so many times. Jackson thought that the magmas should change with time because of the large volume (35,000 km^3 per volcanic shield) of magma piled on the old (Cretaceous?) sea floor. The age of the floor and average composition of each shield are still unknown. Presumably a convective plume could replenish the supply of similar magma throughout the time period required.

The double, isolated, lava pile of the island of Reunion, about 100,000 km^3 in volume [described by B. G. J. Upton (University of Edinburgh, Scotland)] is distinctive in that it is probably not part of an archipelago, it is less voluminous than the Hawaiian chain, the rocks are predominantly transitional tholeiites with higher K_2O, and it apparently was formed at a slower rate. Upton's calculations indicated that the pile originated at a considerable distance (200 to 500 km) from the spreading center of the Indian Ocean. He also emphasized the need to date the floor upon which the island rests.

Trench-Arc System

The geometry of the plate as it sinks down into the mantle at certain trenches could be outlined. The question of whether the sediment on an ocean plate was scraped off, became metamorphosed and attached to the adjoining plate, thereby extending the continents, or went down, to be melted up with the basalt was the subject of debate. It was evident that all subduction zones differ in character. Some had relatively well-defined earthquake patterns and others exhibited highly dispersed earthquake centers down to great depths (250 km), according to D. E. James (Department of Terrestrial Magnetism, Carnegie Institution of Washington). The topology of the measured earthquake or Benioff zone segments is quite variable compared with the common inclined plane of 45°. It was not clear just where the earthquake zone was situated within the plate or if the plate could still be identified to the depths of the deepest quakes (700 km). The critical evidence that the plate is down there at all is primarily based on the attenuation of seismic waves and the 6 to 7 percent increase in velocity within the plate, according to Jack E. Oliver (Columbia University, New York). Results of calculations on deep and intermediate focal plane mechanisms supported the view that the plate is sinking. The increasing grade of relatively high-pressure metamorphism found across some belts of outcropping rocks in the arcs was believed by W. G. Ernst (University of California, Los Angeles) to indicate the direction of plate motion. Great emphasis was put on the blueschists as an indicator of a descending plate. There was little doubt that such metamorphosed (low-temperature and high-pressure) sediments and volcanics had to be carried down quickly *and* brought back up quickly to avoid being severely metamorphosed. He cited the west coast of the United States, southwestern Japan, and the Alps as examples of such regions. Heated debate arose over the actual thickness of the plate with values ranging from 50 to 200 km. The decoupling of the lithosphere from the asthenosphere was assumed by some to take place within the low-velocity zone where partial melting initiates. It was particularly interesting to note the deemphasis on the Moho as a critical boundary. The formerly popular eclogite-basalt transition was also demoted to a relatively insignificant event quantitatively.

It appeared to be simple to draw isotherms for a cold plate underthrusting an adjoining plate. The first volcanoes appear about 175 ± 75 km (based on 50 examples) behind the trench, according to W. R. Dickinson (Stanford University, Stanford, Calif.). Most participants accepted the notion that water was involved in the production of the magmas under the arcs and that its source was the downgoing plate. Others thought the water was coming from the rocks in the adjoining convective cell involving continental materials rich in both water and alkalies. Water lowers the temperature of the *beginning* of melting (the solidus) drastically compared with that required for the presumably dry melting under the ridges, but the temperatures of complete melting (the liquidus) may differ by only 150°C. No matter what the source of the lavas pouring out along the arcs, the trace element chemistry was a constant reminder of the lack of knowledge of the processes operating. Even the alleged increase in K_2O in lavas formed at increasing depth to the Benioff zone was viewed with some skepticism.

Rifts, Batholiths, and Ophiolites

The rift environment was contrasted to the ridge environment. Rifts may be precursors of general ridge and ocean formation, but many seem to be abortive attempts to form new ocean basins. Fossil rifts were identified mainly on the basis of the large volumes of two contrasted groups of highly alkaline volcanics associated with rift formation. Such alkalic rocks indicated to some that the spreading rates were slow and that an ocean basin would not necessarily be produced. Some thought that the real precursors to rifting were the large flood basalts such as those covering the Deccan of India.

The East African Rift System was described by J. Barry Dawson (University of St. Andrews, Scotland), who noted its confinement to an upwarp structure and lack of continuity in detail. Other similar upwarp structures in Africa had no rifts or were post-extension. The relatively low velocity (7.8 km/sec) under the rift and shallow depth to Moho was related to the igneous activity concentrated in the rift, but upwarp or magmatic activity, or both, are regarded as surface manifestations of mantle processes.

Batholith formation was added to the list of criteria for recognizing old plate boundaries by Gilluly. It was pointed out by H. R. Shaw (U.S. Geological Survey, Washington, D.C.) that batholith development took place under other circumstances as well. The Basin and Range province of western United States has, for example, younger plutons than the west coast. The importance of water in the generation of batholiths was emphasized by P. J. Wyllie (University of Chicago). Of particular interest now is the "spreading out" of the melting range of rocks such as granite with decreasing water content.

The ophiolite series of rocks, according to E. Moores (University of California, Davis), is an indicator of the existence of a previous ocean basin. A major question involved the early emplacement of the ophiolite sequence in an orogeny, perhaps as an upthrust of the basement. Its dismembered character indicated involvement in the subsequent motions. An appeal was made for an experimental study of the partial melting behavior of peridotite at low pressures to determine whether the ophiolite sequence was indeed a possible product. J. S. Dickey (Geophysical Laboratory) was particularly interested in identifying peridotites which are barren of the basaltic components. In the peridotite bodies in the western Mediterranean, for example, the basaltic components are retained as layers within the peridotite. The criteria for identifying the existence of old ridges were based primarily on the existence of primitive basalts, dike swarms, and ophiolites, whereas the subduction zones were indicated by blueschists and batholiths. B. G. J. Upton suggested that there was a major separation of plates 1050 to 1250 million years ago, an idea based on his analysis of the relations in south Greenland, Labrador, and the Lake Superior area. It was clear that one of the major efforts in the future would be the delineation of plates in the Precambrian.

Conclusion

Petrologists can make significant contributions to the plate tectonic concept. Fixing the stability fields of the principal rock types involved will provide the limits of pressure and temperature of the various environments. Experimental determination of the partition coefficients of the trace elements will be helpful. Studies of the partial melting behavior of possible parental materials in the absence and presence of water, especially the undersaturated region, will contribute to the understanding of magma production. Experimental observations on the rheological properties of the peridotites below and just above the solidus will lead to a better evaluation of the convective mechanism. Measurement of the fundamental properties of rocks, such as the density of solids and liquids at high pressures and temperatures, would contribute to understanding the concepts of diapiric rise, magma segregation, and the low-velocity zone. Broader rock sampling of the oceanic areas of all environments will do much to define the petrologic provinces. The field petrologist specializing in the Paleozoic regions and Precambrian shields can contribute by examining those regions for old plate boundaries and devising new criteria for their recognition.

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