# Seismology and the New Global Tectonics[1]

BRYAN ISACKS AND JACK OLIVER

*Lamont Geological Observatory, Columbia University, Palisades, New York 10964*

LYNN R. SYKES[2]

*Earth Sciences Laboratories, ESSA*
*Lamont Geological Observatory, Columbia University, Palisades, New York 10964*

A comprehensive study of the observations of seismology provides widely based strong support for the new global tectonics which is founded on the hyptheses of continental drift, sea-floor spreading, transform faults, and underthrusting of the lithosphere at island arcs. Although further developments will be required to explain certain part of the seismological data, at present within the entire field of seismology there appear to be no serious obstacles to the new tectonics. Seismic phenomena are generally explained as the result of interactions and other processes at or near the edges of a few large mobile plates of lithosphere that spread apart at the ocean ridges where new surficial materials arise, slide past one another along the large strike-slip faults, and converge at the island arcs and arc-like structures where surficial materials descend. Study of world seismicity shows that most earthquakes are confined to narrow continuous belts that bound large stable areas. In the zones of divergence and strike-slip motion, the activity is moderate and shallow and consistent with the transform fault hypothesis; in the zones of convergence, activity is normally at shallow depths and includes intermediate and deep shocks that grossly define the present configuration of the down-going slabs of lithosphere. Seismic data on focal mechanisms give the relative direction of motion of adjoining plates of lithosphere throughout the active belts. The focal mechanisms of about a hundred widely distributed shocks give relative motions that agree remarkably well with Le Pichon's simplified model in which relative motions of six large, rigid blocks of lithosphere covering the entire earth were determined from magnetic and topographic data associated with the zones of divergence. In the zones of convergence the seismic data provide the only geophysical information on such movements.

Two principal types of mechanisms are found for shallow earthquakes in island arcs: The extremely active zone of seismicity under the inner margin of the ocean trench is characterized by a predominance of thrust faulting, which is interpreted as the relative motion of two converging plates of lithosphere; a less active zone in the trench and on the outer wall of the trench is characterized by normal faulting and is thought to be a surficial manifestation of the abrupt bending of the down-going slab of lithosphere. Graben-like structures along the outer walls of trenches may provide a mechanism for including and transporting sediments to depth in quantities that may be very significant petrologically. Large volumes of sediments beneath the inner slopes of many trenches may correspond, at least in part, to sediments scraped from the crust and deformed in the thrusting.

Simple underthrusting typical of the main zone of shallow earthquakes in island arcs does not, in general, persist at great depth. The most striking regularity in the mechanisms of intermediate and deep earthquakes in several arcs is the tendency of the compressional axis to parallel the local dip of the seismic zone. These events appear to reflect stresses in the relatively strong slab of down-going lithosphere, whereas shearing deformations parallel to the motion of the slab are presumably accommodated by flow or creep in the adjoining ductile parts of the mantle. Several different methods yield average rates of underthrusting as high as 5 to 15 cm/yr for some of the more active arcs. These rates suggest that temperatures low enough to permit dehydration of hydrous minerals and hence shear fracture may persist even to depths of 700 km. The thickness of the seismic zone in a part of the Tonga arc where very precise hypocentral locations are available is less than about 20 km for a wide range of depths. Lateral variations in thickness of the lithosphere seem to occur, and in some areas the lithosphere may not include a significant thickness of the uppermost mantle.

[1] Lamont Geological Observatory Contribution 1234.
[2] Order of authors determined by lot.

The lengths of the deep seismic zones appear to be a measure of the amount of under thrusting during about the last 10 m.y. Hence, these lengths constitute another 'yardstick' for investigations of global tectonics. The presence of volcanism, the generation of many tsunamis (seismic sea waves), and the frequency of occurrence of large earthquakes also seem to be related to underthrusting or rates of underthrusting in island arcs. Many island arcs exhibit a secondary maximum in activity which varies considerably in depth among the various arcs. These depths appear, however, to correlate with the rate of underthrusting, and the deep maxima appear to be located near the leading (bottom) part of the down-going slab. In some cases the down-going plates appear to be contorted, possibly because they are encountering a more resistant layer in the mantle. The interaction of plates of lithosphere appears to be more complex when all the plates involved are continents or pieces of continents than when at least one plate is an oceanic plate. The new global tectonics suggests new approaches to a variety of topics in seismology including earthquake prediction, the detection and accurate location of seismic events, and the general problem of earth structure.

## Introduction

This paper relates observations from the field of seismology and allied disciplines to what is here termed the 'new global tectonics.' This term is used to refer in a general way to current concepts of large-scale tectonic movements and processes within the earth, concepts that are based on the hypotheses of continental drift [*Wegener,* 1966], sea-floor spreading [*Hess,* 1962; *Dietz,* 1961], and transform faults [*Wilson,* 1965*a*] and that include various refinements and developments of these ideas. A comprehensive view of the relationship between seismology and the new global tectonics is attempted, but there is emphasis on data from earthquake seismology, as opposed to explosion seismology, and on a particular version of the sea-floor spreading hypothesis in which a mobile, near-surface layer of strength, the lithosphere, plays a key role. Two basic questions are considered. First, do the observations of seismology support the new global tectonics in some form? To summarize briefly, they do, in general, give remarkable support to the new tectonics. Second, what new approaches to the problems of seismology are suggested by the new global tectonics? There are many; at the very least the new global tectonics is a highly stimulating influence on the field of seismology; very likely the effect will be one of revolutionary proportions.

The mobile lithosphere concept is based partly on an earlier study [*Oliver and Isacks,* 1967], but, as presented here, it incorporates ideas from *Elsasser* [1967], who independently developed a model with many similar features based on entirely different considerations, and ideas from *Morgan* [1968] and *Le Pichon* [1968], who pursued this concept further by investigating the relative motion in plan of large blocks of lithosphere.

Figure 1 is a block diagram illustrating some of the principal points of the mobile lithosphere hypothesis. In a relatively undisturbed section, three flat-lying layers are distinguished: (1) the *lithosphere,* which generally includes the crust and uppermost mantle, has significant strength, and is of the order of 100 km in thickness; (2) the *asthenosphere,* which is a layer of effectively no strength on the appropriate time scale and which extends from the base of the lithosphere to a depth of several hundred kilometers; and (3) the *mesosphere,* which may have strength and which makes up the lower remaining portion of the mantle and is relatively passive, perhaps inert, at present, in tectonic processes. (Elsasser refers to the lithosphere as the tectosphere and defines some other terms somewhat differently, but the terminology of *Daly* [1940] is retained here. The term 'strength,' which has many definitions and connotations, is used here, following Daly, in a general sense to denote enduring resistance to a shearing stress with a limiting value.) The boundaries between the layers may be gradational within the earth. The asthenosphere corresponds more or less to the low-velocity layer of seismology; it strongly attenuates seismic waves, particularly high-frequency shear waves. The lithosphere and the mesosphere have relatively high seismic velocities and propagate seismic waves without great attenuation.

At the principal zones of tectonic activity within the earth (the ocean ridges, the island arc or island-arc-like structures, and the major

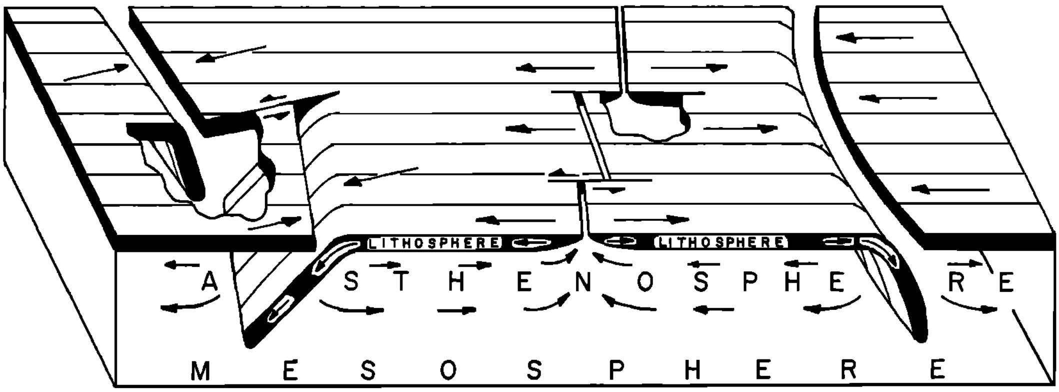



Fig. 1. Block diagram illustrating schematically the configurations and roles of the lithosphere, asthenosphere, and mesosphere in a version of the new global tectonics in which the lithosphere, a layer of strength, plays a key role. Arrows on lithosphere indicate relative movements of adjoining blocks. Arrows in asthenosphere represent possible compensating flow in response to downward movement of segments of lithosphere. One arc-to-arc transform fault appears at left between oppositely facing zones of convergence (island arcs), two ridge-to-ridge transform faults along ocean ridge at center, simple arc structure at right.

strike-slip faults) the lithosphere is discontinuous; elsewhere it is continuous. Thus, the lithosphere is composed of relatively thin blocks, some of enormous size, which in the first approximation may be considered infinitely rigid laterally. The major tectonic features are the result of relative movement and interaction of these blocks, which spread apart at the rifts, slide past one another at large strike-slip faults, and are underthrust at island arcs and similar structures. *Morgan* [1968] and *Le Pichon* [1968] have demonstrated in a general way and with remarkable success that such movement is self-consistent on a worldwide scale and that the movements agree with the pattern of sea-floor spreading rates determined from magnetic anomalies at sea and with the orientation of oceanic fracture zones. *McKenzie and Parker* [1967] used the mobile lithosphere concept to explain focal mechanisms of earthquakes, volcanism, and other tectonic features in the northern Pacific.

Figure 1 also demonstrates these concepts in block diagram form. Near the center of the figure the lithosphere has been pulled apart, leaving a pattern of ocean ridges and transform faults on the surface and a thin lithosphere thickening toward the flanks beneath the ridge as the new surface material cools and gains strength. To the right of the diagram the lithosphere has been thrust, or has settled, beneath an island arc or a continental margin that is currently active. At an inactive margin the lithosphere would be unbroken or healed. The left side of the diagram shows two island-arc structures, back to back, with the lithosphere plunging in a different direction in each case and with a transform fault between the structures. Whereas the real earth must be more complicated, particularly at this back-to-back structure, this figure represents, in a general way, a part of the Pacific basin including the New Hebrides, Fiji, Tonga, the East Pacific rise, and western South America.

The counterflow corresponding to movement of the lithosphere into the deeper mantle takes place in the asthenosphere, as indicated schematically by the appropriate arrows in the figure. To what extent, if any, there is flow of the adjoining upper part of the asthenosphere in the same direction as the overlying lithosphere is an important but open question, partially dependent on the definition of the boundary. A key point of this model is that the pattern of flow in the asthenosphere may largely be controlled by the configurations and motions of the surface plates of lithosphere and not by a geometrical fit of convection cells of simple shape into an idealized model of the earth. It is tempting to think that the basic driving mechanisms for this process is gravitational instability resulting from surface cooling and hence a relatively high density of near-surface mantle materials. Thus, convective circulation in the upper mantle might occur as thin blocks of lithosphere of large horizontal dimensions slide laterally over large distances as they descend; a compensating return flow takes place in the asthenosphere. The process in the real earth must be more complex than this simple model, however. The reader is referred to *Elsasser* [1967] for a discussion of many points relating to this problem.

Alternatively, the surface configuration might be taken as the complicated response of the strong lithosphere to relatively simple convection patterns within the asthenosphere. Thus, the basic question whether the lithosphere or the asthenosphere may be thought of as the active element, with the other being passive, is not yet resolved. Probably, however, there has been a progressive thinning of the convective zone with time, deeper parts of the mantle having also been involved during early geologic time.

Figure 2, adapted from *Le Pichon* [1968] with additions, shows the plan of blocks of lithosphere as chosen by Le Pichon for the spherical earth and indicates how their movements are being accommodated on a worldwide scale. The remarkably detailed fit between this scheme, based on a very small number of rigid blocks of lithosphere (six) and the data of a number of fields, is very impressive. The number and configuration of the blocks of lithosphere is surely larger than six at present and almost certainly the pattern has changed within geologic time, but the present pattern must, in general, be representative of at least the Quaternary and late Tertiary. The duration of the current episode of sea-floor spreading is not known. Some evidence suggests that it began in the Mesozoic and has continued rather steadily to the present. Other evidence [*Ewing and Ewing,* 1967] indicates that the most recent episode of spreading began about 10 m.y. ago. This suggestion is considered here because it opens new possibilities for explaining certain seismological observations, particularly the configuration of the deep earthquake zones. Other explanations for such evidence are also considered, however.

With this one very simple version of the new global tectonics as background it is possible to begin considering the data, but in this process it soon becomes evident that much more detailed information on the earth is available and that the hypothesis and the earth model can be developed much further. These developments are presented later in the text as the relevant data are discussed.

This paragraph gives a brief review of some of the developments leading to the new global tectonics. A number of contributions vital to the development of the current position on this topic are cited, but the review is not intended to be comprehensive. The literature bearing on this topic is voluminous, is widespread in space and time, and differs in degree of relevance, so that a thorough documentation of its development is a job for a historian, not a scientist. The hypothesis of continental drift had a substantial impact on the field of geology when it was proposed in 1929 by *Wegener* [1966], but until recently it had not received general acceptance, largely because no satisfactory mechanism had been proposed to explain the movement, without substantial change of form, of the continents through the oceanic crust and upper mantle. When many new data became available, particularly in the fields of marine geology and geophysics, *Hess* [1962] and *Dietz* [1961] proposed that the sea floor was spreading apart at the ocean ridges so that new 'crust' was being generated there while older 'crust' was disappearing into the mantle at the sites of the ocean trenches. The driving mechanism for this spreading was thought to be convection within the mantle. The remarkable success with which the hypothesis of sea-floor spreading accommodated such diverse geologic observations as the linear magnetic anomalies of the ocean [*Vine and Matthews,* 1963; *Pitman and Heirtzler,* 1966], the topography of the ocean floor [*Menard,* 1965], the distribution and configuration of continental margins and various other land patterns [*Wilson,* 1965*a*; *Bullard,* 1964; *Bullard et al.,* 1965], and certain aspects of deep-sea sediments [*Ewing and Ewing,* 1967] raised this hypothesis to a level of great importance and still greater promise. The contributions of seismology to this development have been substantial, not only in the form of general information on earth structure but also in the form of certain studies that bear especially on this

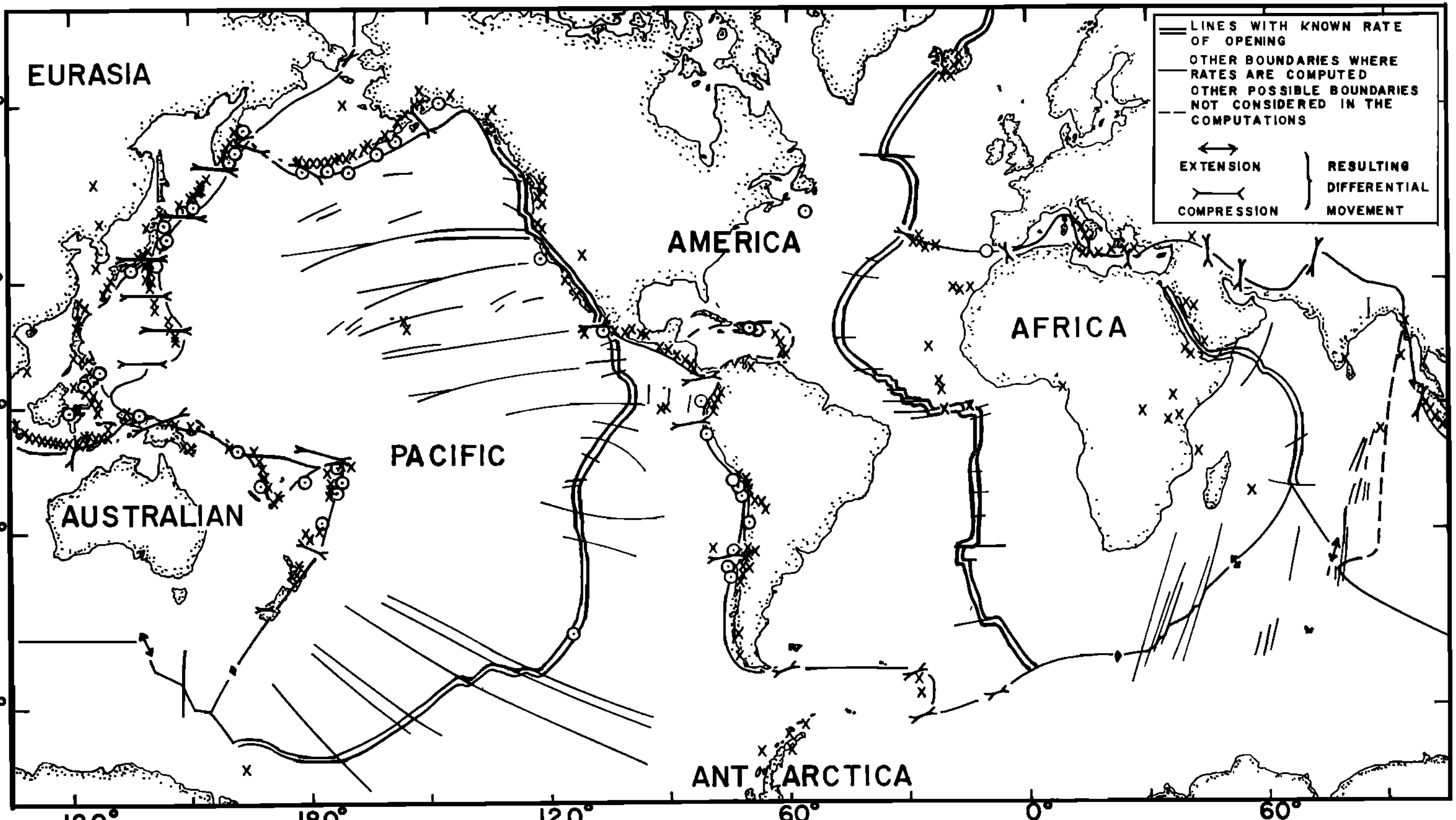



Fig. 2. Computed rates of compression and extension along boundaries of six lithospheric blocks [after *Le Pichon*, 1968]. Computed movements were derived from rates of spreading determined from magnetic data and from orientations of fracture zones along features indicated by double lines. The extensional and compressional symbols in the legend represent rates of 10 cm/yr; other similar symbols are scaled proportionally. Symbols appearing as diamonds represent small computed rates of extension for which the arrowheads coalesced. Historically active volcanoes [*Gutenberg and Richter*, 1954] are denoted by crosses. Open circles represent earthquakes that generated tsunamis (seismic sea waves) detected at distances of 1000 km or more from the source.

hypothesis. Two specific examples are *Sykes*'s [1967] evidence on seismicity patterns and focal mechanisms to support the transform fault hypothesis of *Wilson* [1965a] and *Oliver and Isacks*'s [1967] discovery of anomalous zones that appear to correspond to underthrust lithosphere in the mantle beneath island arcs.

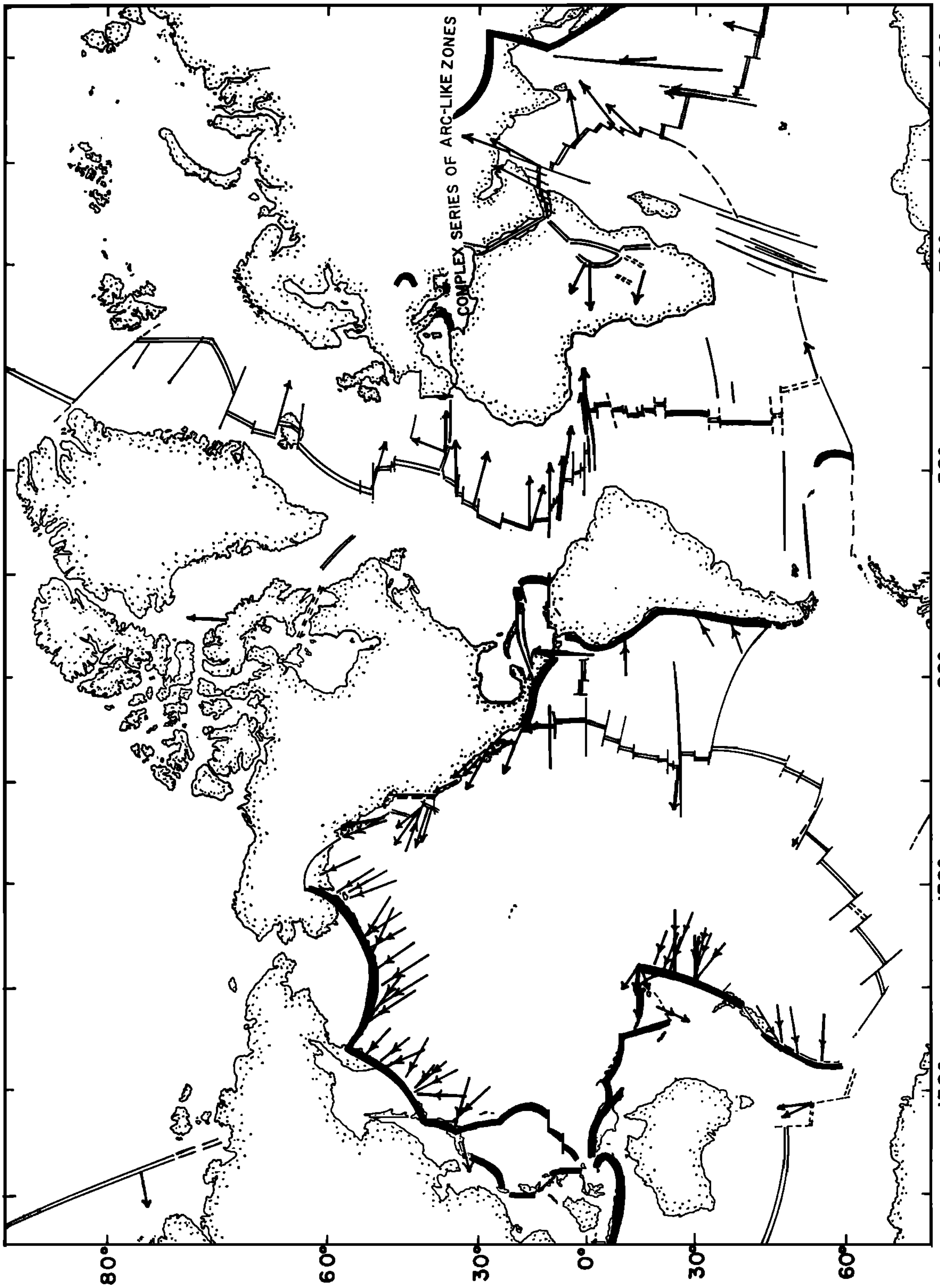
There are many important seismological facts that are so apparent that they are commonly accepted without much concern as to their origin; they fall into place remarkably well under the new global tectonics. For example, the general pattern of seismicity, which consists of a number of continuous narrow active belts dividing the earth's surface into a number of stable blocks, is in accord with this concept. In part this agreement is by design, for the blocks were chosen to some extent on this basis, but data from other fields were used as well. That the end result is internally consistent is significant. Zones predicted by the theory to be tensional, such as ocean rifts, are sites of only shallow earthquakes (the thin shallow lithosphere is being pulled apart; earthquakes cannot occur in the asthenosphere), and the general level of seismic activity and the size of the largest earthquakes are lower there than in the more active compressional features. In the compressional features (the arcs) large, deep earthquakes occur and activity is high as the lithosphere plunges into the deeper mantle eventually to be absorbed. Deep earthquakes can occur only where former crustal and uppermost mantle materials are now found in the mantle. Where one block of the lithosphere is moving past another along the surface at the zones of large strike-slip faulting, seismic activity is shallow, but occasional rather large shallow earthquakes are observed. Some zones combine thrusting and strike-slip motion. The general pattern of earthquake focal mechanisms is in remarkable agreement with the pattern predicted by the movements of the lithosphere determined in other ways and provides much additional information on this process. The depth of the deepest earthquakes (about 700 km) has been reasonably well known, but unexplained, for many years. The mobile lithosphere hypothesis offers, at this writing, several possible alternatives to explain this observation. Many similar points are raised in the remainder of this paper. Other hypotheses on global tectonics, for example, the expanding earth and the contracting earth hypotheses, have been far less satisfactory in explaining seismological phenomena.

Certainly the most important factor is that the new global tectonics seem capable of drawing together the observations of seismology and observations of a host of other fields, such as geomagnetism, marine geology, geochemistry, gravity, and various branches of land geology, under a single unifying concept. Such a step is of utmost importance to the earth sciences and will surely mark the beginning of a new era.

In the remainder of this paper, the relationship between the new global tectonics and the field of seismology is discussed for a variety of topics ranging from seismicity to tsunamis, from earth structure to earthquake prediction. In each case what the authors judge to be representative, reliable evidence from the field of seismology is presented. This judgment is based on the quality of raw data and their analysis, not on the relation of the results to the new global tectonics. Reasonable speculation is presented where it seems proper. The organization of the paper is based not on the classical divisions of seismology but on the principal effects predicted by the new global tectonics and relevant to seismology. As a result of the remarkable capacity of the new global tectonics for unification, an obvious division of material among the sections was not completely achieved, however.

The first two sections present seismological evidence that the worldwide rift system and island arcs are the sources and sinks, respectively, for surficial material. The third section on compatibility of movements on a worldwide scale is closely related to the first two sections.

Fig. 3. (*Opposite*) Summary map of slip vectors derived from earthquake mechanism studies. Arrows indicate horizontal component of direction of relative motion of block on which arrow is drawn to adjoining block. Crests of world rift system are denoted by double lines; island arcs, and arc-like features, by bold single lines; major transform faults, by thin single lines. Both slip vectors are shown for an earthquakes near the western end of the Azores-Gibraltar ridge since a rational choice between the two could not be made. Compare with directions computed by Le Pichon (Figure 2).


COMPLEX SERIES OF ARC-LIKE ZONES
90°
30°
30°
90°
150°
150°
80°
60°
30°
0°
30°
60°

Evidence from seismology on the structure of the mantle in terms of a lithosphere, an asthenosphere, and a mesosphere is so voluminous and well known that the section on this topic, the fourth section, presents primarily additional evidence of particular relevance to the new global tectonics. The fifth section, on the impact of the new global tectonics on seismology, is less documented by data than the previous sections partly because the impact of the new global tectonics is quite recent. The natural lag in pursuing this aspect is such that there has been to date relatively little emphasis in this particular field. This section is, then, somewhat speculative and, hopefully, provocative.

Few scientific papers are completely objective and impartial; this one is not. It clearly favors the new global tectonics with a strong preference for the mobile lithosphere version of this subject. In the final section, however, we report an earnest effort to uncover reliable information from the field of seismology that might provide a case against the new global tectonics. There appears to be no such evidence. This does not mean, however, that many of the data could not be explained equally well by other hypotheses (although probably not so well by any other single hypothesis) or that further development or modification of the new global tectonics will not be required to explain some of the observations of seismology. It merely means that, at present, in the field of seismology, there cannot readily be found a major obstacle to the new global tectonics.

## Mid-Ocean Ridges—the Sources

*Displacements along fracture zones.* Recent studies of earthquakes have revealed several important facts about the nature of displacements on the ocean floor [*Sykes*, 1967, 1968]. The recognition of the worldwide extent of the mid-ocean ridge system (Figures 2 and 3) [*Ewing and Heezen*, 1956] led to a great interest in the significance of this major feature to global tectonics. Although the ridge system appears to be a continuous feature on a large scale, the crest of the ridge is actually discontinuous in a number of places (Figures 1, 2, and 3). These discontinuities correlate with the intersections of the ridge and the major fracture zones—long linear zones of rough topography that resemble major fault zones on the continents. The apparent displacements along these fracture zones have been explained in at least three different ways, including simple offset of the ridge by strike-slip faulting [*Vacquier*, 1962], in situ development of the ridge crests at separate locations accompanied by normal faulting along fracture zones [*Talwani et al.*, 1965*b*], and transform faulting [*Wilson*, 1965*a*].

*Transform faults.* Although the concept of simple offset tacitly assumes the conservation of surface area, the growth or the destruction of surface area is basic to the definition of the transform fault. In this hypothesis the active portion (BC in Figure 4) of a strike-slip fault along which large horizontal displacement has occurred ends abruptly at the crest of a growing ocean ridge. The horizontal displacement along the fault is transformed (or absorbed) by seafloor growth on the ridge; the growing ridge is, in turn, terminated by the fault. Two separate segments of ridge crest can be joined (Figure 4) by a strike-slip fault of this type; these faults are called transform faults of the ridge-ridge type.

*Wilson* [1965*a*] recognized that the sense of

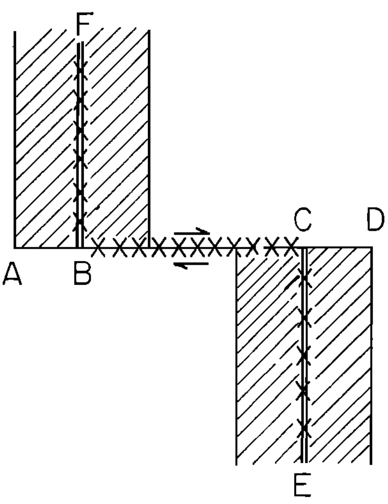



Fig. 4. An idealized model of sea-floor spreading and transform faulting of the ridge-ridge type. Hatching indicates new surface area created during a given period of sea-floor spreading along the active ridge crests BF and CE. Present seismicity (indicated by crosses) is confined to ridge crests and to segment BC of the fracture zone AD. Arrows denote sense of shear motion along active segment BC.

shear displacement along transform faults of the ridge-ridge type would be exactly opposite that required for a simple offset of the two segments of ridge crest. He also pointed out that seismic activity along transform faults should be confined to the region between the two ridge crests (segment BC in Figure 4). If the crestal zones are being displaced by simple offset, however, seismic activity should be present along the entire length of the fracture zone.

*Earthquake mechanisms.* The first motions of seismic waves from earthquakes offer a means for ascertaining the sense and type of displacements on fracture zones. First-motion studies are often called 'fault-plane solutions' or 'focal-mechanism solutions.' Although many earth scientists have been disappointed by the large uncertainties involved in many first-motion studies, investigations of focal mechanisms were vastly upgraded by the installation of the World-Wide Standardized Seismograph Network [*Murphy*, 1966]. Reliable calibration, availability of data, high sensitivity, use of seismographs of both long and short periods, and greater geographical coverage are some of the more important characteristics of this network, which commenced operation in 1962. Various studies using data from these stations have confirmed that a double couple (or a shear dislocation) is an appropriate model for the radiation field of earthquakes [*Stauder*, 1967; *Isacks and Sykes*, 1968]. Hence, the first motions observed at seismograph stations around the world may be used to determine the orientation and the sense of the shear motion at the sources of earthquakes in various tectonic regions. Additional background information on earthquake mechanisms will be introduced in later sections as further clarification is required.

*Mechanisms along world rift system.* *Sykes* [1967] examined the focal mechanisms of seventeen earthquakes along various parts of the world rift system. In his study all the earthquakes located on fracture zones were characterized by a predominance of strike-slip motion. In each case the shear motion was in the correct sense for transform faulting (Figure 4), but it was consistently opposite in sense to that expected for simple offset. This is an instance in the earth sciences in which a yes-or-no answer could be supplied by data analysis. The sense of motion (left lateral) along one of the major fracture zones of the East Pacific rise (a branch of the mid-ocean ridge system) is illustrated in Figure 1.

Sykes also showed that earthquakes located on the ridge crests (segments BF and CE in Figure 4) but not located on fracture zones are characterized by a predominance of normal faulting. Normal faulting on ocean ridges had long been suspected because of the existence of a rift valley near the crest of large portions of the ridge system [*Ewing and Heezen*, 1956]. More than fifty mechanism solutions (Figure 3) have now been obtained for the world rift system [*Sykes*, 1968; *Tobin and Sykes*, 1968; *Banghar and Sykes*, 1968]; they continue to confirm the pattern of transform faulting and normal faulting described by Sykes. Nearly the same tectonic phenomenon is observed for each of the major oceans.

*Seismicity.* The distribution of earthquakes is another key piece of seismic evidence for the hypothesis of transform faulting. Nearly all the earthquakes on the mid-ocean ridges are confined either to the ridge crests or to the parts of fracture zones that lie between ridge crests [*Sykes*, 1967]. Seismic activity along a fracture zone ends abruptly (Figure 4) when the fracture zone encounters a ridge; only a few earthquakes have been detected from the outer parts (segments AB and CD) of most fracture zones. If the transform fault theory is correct, the areas of sea floor that are now bounded by the outer inactive parts of fracture zones were once located between two ridge crests; these blocks of sea floor moved beyond either crest as spreading progressed. Thus, the age of deformation becomes older as the distance from an active crest increases.

*Earthquake swarms.* The occurrence of earthquake swarms along the world rift system suggests that the crestal zone probably is characterized by submarine volcanic eruptions [*Sykes et al.*, 1968]. Earthquake swarms are a distinctive sequence of shocks highly grouped in space and time with no one outstanding principal event. Although these sequences sometimes occur in nonvolcanic regions, most of the world's earthquake swarms are concentrated in areas of present volcanism or geologically recent volcanism [*Richter*, 1958; *Minikami*, 1960]. Large swarms often occur before volcanic eruptions or accompanying them; smaller swarms may be indicative of magmatic activity that failed to reach the surface as an eruption.

From the seismograph records at Palisades, New York, *Sykes et al.* [1968] recognized more than twenty swarms of earthquakes occurring during the past 10 years. These swarms commonly lasted a few hours or a few days. Although many of the larger earthquakes along the world rift system occur on fracture zones and are characterized by strike-slip faulting, nearly all the swarms are restricted to the ridge crests (segments BF and CE in Figure 4) and seem to be characterized by normal faulting. Swarms are commonly (but not always) associated with volcanic eruptions on islands or on or near the crest of the world rift system.

From a simulation of magnetic anomalies *Matthews and Bath* [1967] *and Vine and Morgan* [1967] estimate that most of the new surface material along the world rift system is injected within a few kilometers of the axis of the ridge. In Iceland, where the rift may be seen and studied in detail, postglacial volcanism is confined largely to the median rift that crosses the island [*Bodvarsson and Walker*, 1964]. The rift apparently marks the landward continuation of the crest of the mid-Atlantic ridge (Figures 2 and 3).

The lack of weathering in rock samples, the young ages measured by radioactive and paleontologic dating of rocks and core materials, and the general absence of sediment as revealed by bottom photographs and by reflection profiling all attest to the youthful character of the crestal zones of the mid-ocean ridge [*Ewing et al.*, 1964; *Burckle et al.*, 1967; *van Andel and Bowin*, 1968; *Dymond and Deffeyes*, 1968]. Thus, the occurrence of earthquake swarms is compatible with the hypothesis that new surface materials are being emplaced magmatically near the axes of the ocean ridges. The large earthquake swarms (and perhaps some of the smaller swarms) may be indicative of eruptions or magmatic processes in progress near the ridge crests. Nonetheless, more work is needed to ascertain if a causal relationship exists between the two phenomena.

*Synthesis of data for ridges.* Seismological evidence of various types seems to provide a definitive argument for the hypotheses of transform faulting and sea-floor spreading on the mid-ocean ridge system. These data are in excellent agreement with evidence of spreading from magnetic anomalies, ages of rocks, and the distribution of sediments [*Vine*, 1966; *Heirtzler et al.*, 1968; *Wilson*, 1963; *Burckle et al.*, 1967]. The world rift system must be recognized as one of the major tectonic features of the world. It is characterized nearly everywhere by extensional tectonics, sea-floor growth at its crest, and transform faulting on its fracture zones.

The focal depths and the maximum magnitudes of earthquakes, the narrowness of seismic zones, and the propagation of $S_n$ waves along ocean ridges and transform faults will be described in the sections on worldwide compatability of movements and on additional evidence for the existence of the lithosphere.

*Implications for continental drift.* The similarity of the earthquake mechanisms along nearly the entire length of the ridge system suggests that transform faulting and spreading have been occurring in these regions for extended, but as yet unspecified, periods of time. The distribution of magnetic anomalies, paleomagnetic investigations, and the shapes of continental blocks that supposedly were split apart by spreading furnish a more complete history of the processes of sea-floor spreading and transform faulting. A question of particular interest is: Have the various segments of ridge grown in place; i.e., has the en echelon pattern of ridges and fracture zones prevailed throughout an episode of sea-floor spreading?

Both the Gulf of Aden and the Gulf of California are thought to have opened by continental drift during the last 25 m.y. [*Hamilton*, 1961; *Laughton*, 1966]. If drift occurred in these areas, the displacements are at most a few hundred kilometers. If continental drift can be confirmed for these features, inferences about drift on an ocean-wide scale are placed on a much firmer basis.

Figure 5 shows the distribution of structural features, earthquake epicenters, and earthquake mechanisms for the Gulf of Aden [*Sykes*, 1968]. Nearly all the epicenters are confined either to northeast-striking fracture zones or to the ridge that extends from a branch of the mid-ocean ridge (the Carlsberg ridge) near 9°N, 57°E to the western part of the Gulf of Aden near 12°N, 43°E. This ridge coincides with the rough central zone in Figure 5. As in other parts of the world rift system the earthquakes occurring on

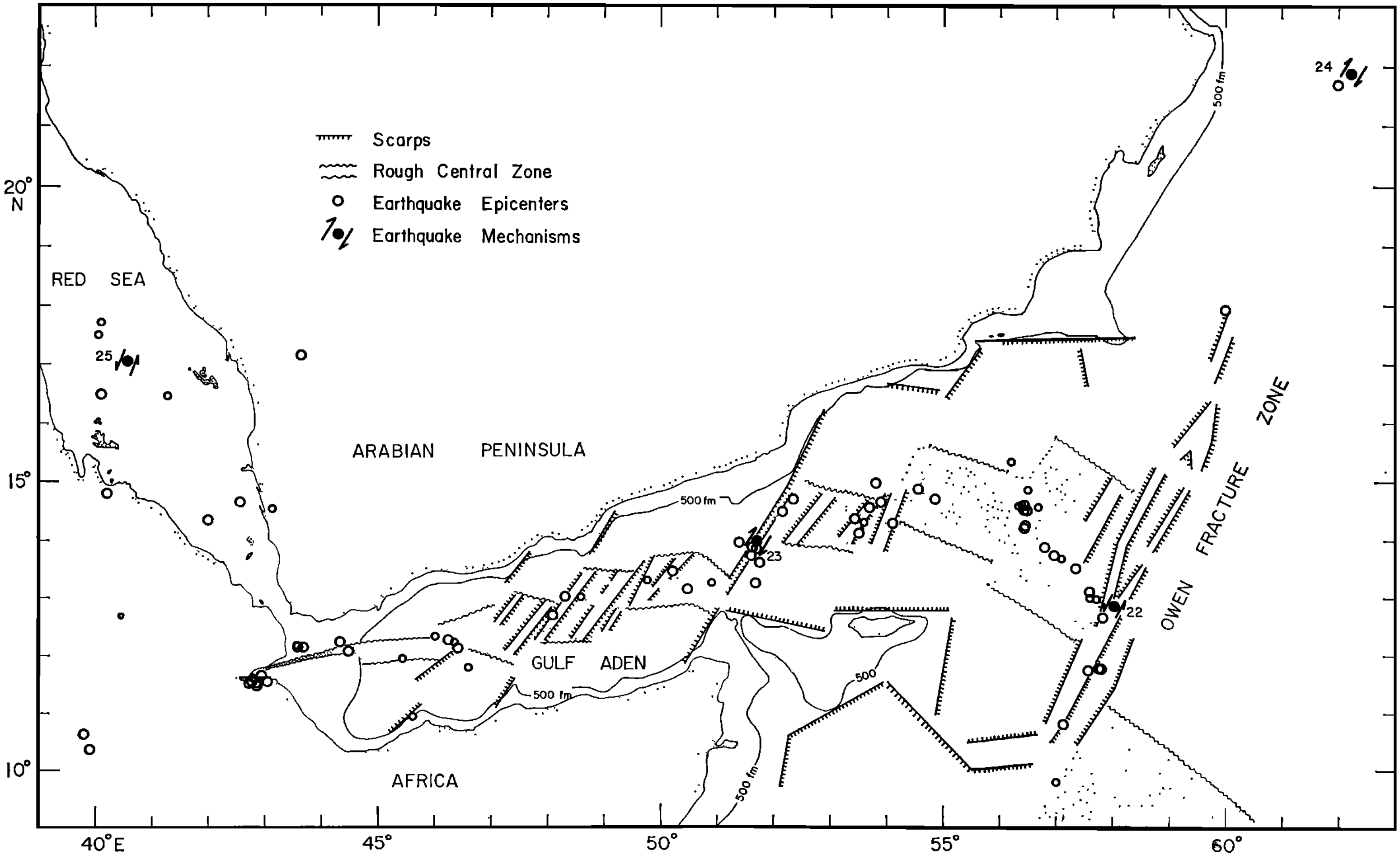



Fig. 5. Structural features of the Gulf of Aden [after *Sykes*, 1968]. Relocated epicenters of earthquakes for the period 1955 to 1966. Scarps and rough central zone after *Laughton* [1966]. Seismicity and focal mechanisms support hypothesis of spreading by ocean ridge-transform fault mechanism.

fracture zones are mostly restricted to the regions between ridge crests. Mechanism solutions for events 22 and 23 (numbers after *Sykes* [1968]) indicate transform faulting of the ridge-ridge type.

If the opening of the Gulf of Aden was accomplished through a simple process of seafloor spreading and transform faulting, the fracture zones should join points in Arabia and in Africa that were together before the drifting commenced. Also, the fracture zones should not continue into the two continental plates. *Laughton* [1966] has shown, in fact, that these faults do not continue inland. In addition, his pre-Miocene reconstruction, in which the two sides of the Gulf of Aden are moved together parallel to the fracture zones, juxtaposes a large number of older structural features on the two sides of the gulf. The en echelon arrangement of segments of ridge is also mirrored in the stepped shape of the continental margins of Arabia and Africa. Hence, the present en echelon pattern seems to have prevailed since the initial breakup of these two blocks about 5 to 25 m.y. ago.

A similar pattern of en echelon ridges is present in the Gulf of California (Figure 6). Earthquake mechanisms from this region are indicative of a series of northwesterly striking transform faults with right-lateral displacement [*Sykes*, 1968]. These transform faults, which are arranged en echelon to the San Andreas fault, connect individual segments of growing ridges in the Gulf of California. Hence, seafloor spreading and transform faulting also were responsible for the displacement of Baja California relative to the mainland of Mexico. If these two blocks are reconstructed by horizontal displacements parallel to the northwesterly striking fracture zones, the peninsula of Baja California is placed in the indentation or 'nitch' of the mainland of Mexico near 21°N, 106°W. Thus, the two pieces appear to fit together in this reconstruction. *Wilson* [1965*a*] has pointed out that the stepped shape of the fracture-zone–ridge pattern in the equatorial Atlantic is mirrored in the stepped shape of the coastlines and the continental margins of Africa and Brazil.

## Island Arcs—The Sinks

Almost anyone who glances casually at a map of the world is intrigued by the organized patterns of the island arcs. The close association of the major ocean deeps with these arcs is obvious and suggests exceptional subsidence in these zones, but other facts are equally striking. Nearly all the world's earthquakes in the deep and intermediate range, most of the world's shallow earthquakes, and the largest departures from isostatic equilibrium are associated with island arcs or arc-like structures, as shown by *Gutenberg and Richter* [1954]. Volcanoes, sea-level changes, folding, faulting, and other forms of geologic evidence also demonstrate the high level of tectonic activity of these features. A concept of global tectonics in which the arcs do not play an important role is unthinkable. If crustal material is to descend into the mantle, the island arcs are suspect as sites of the sinks.

The asymmetrical structure of the arcs and the associated pattern of earthquake occurrence in the mantle led many investigators (e.g., *Vening Meinesz* [1954], *Benioff* [1954], *Hess* [1962], *Dietz* [1961]) to postulate that the structures are the result of compressive stresses normal to the arc and are the sites of vertical movements in various convective schemes. Although such ideas were supported by the investigations of focal mechanisms of earthquakes made by *Honda et al.* [1956] and by the gravity studies of *Vening Meinsz* [1930] and *Hess* [1938], later analyses by *Hodgson* [1957] for focal mechanisms and by *Talwani et al.* [1959] and *Worzel* [1965] for gravity led to different conclusions. This section reviews the data and shows that there is strong support for the compressive nature of island arcs and for their role as sites where surface material moves downward into the mantle. In particular, a variety of evidence supports the model of the arc shown in Figure 1. In this model the leading edge of the lithosphere underthrusts the arc and moves downward into the mantle as a coherent body. The proposed predominance of strike-slip faulting in island arcs [*Hodgson*, 1957] is not in agreement with this model but appears, in view of recent and vastly improved seismic data, to be based on unreliable determinations of focal mechanisms [*Hodgson and Stevens*, 1964]. The extensional features of structures based on gravity and seismic data appear to be surficial and can be reconciled with, and in fact are predicted by, the new hypothesis.

*High-Q and high-velocity zones in the mantle*

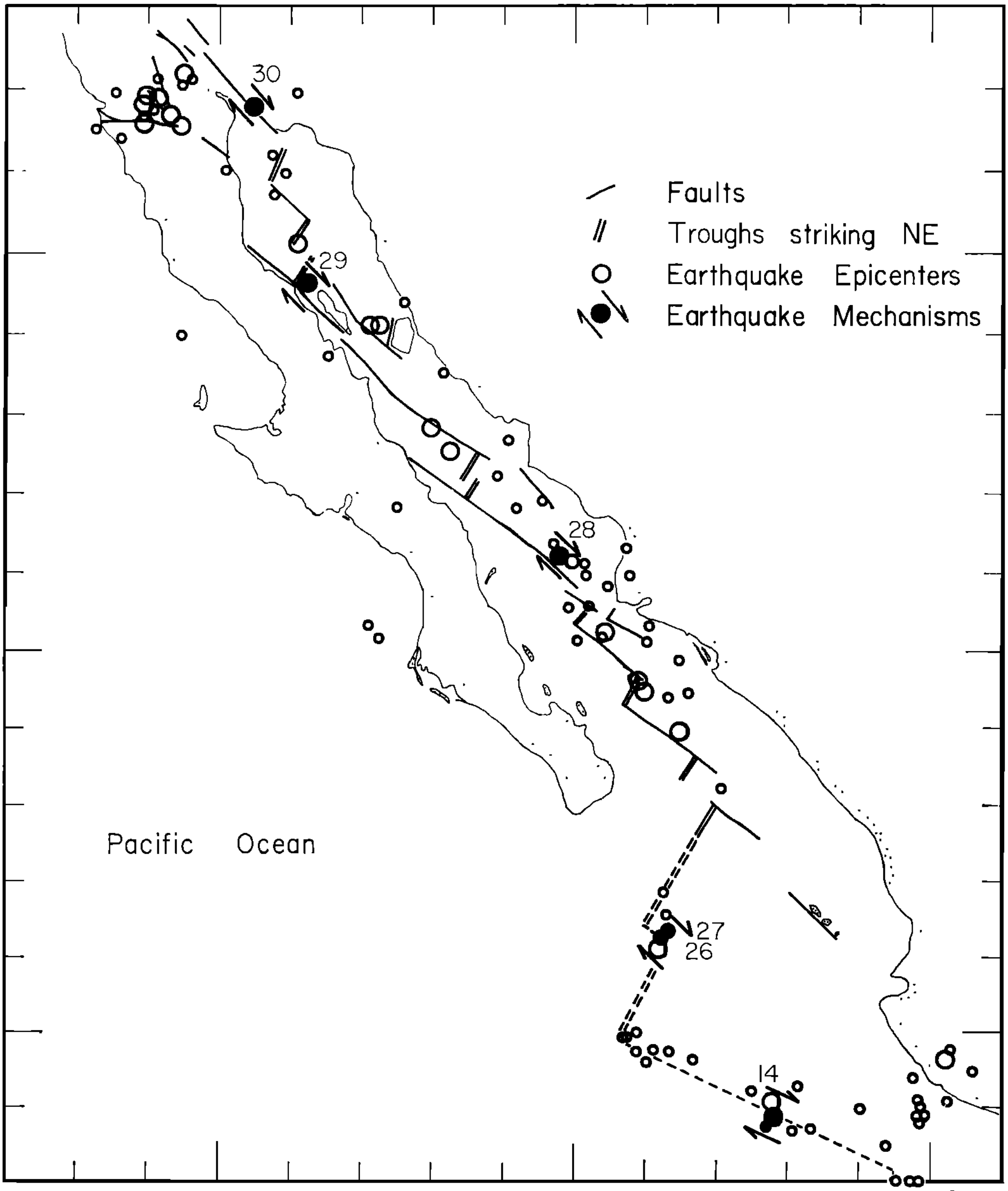



Fig. 6. Structural features of the Gulf of California [after *Sykes*, 1968]. Relocated epicenters of earthquakes for the period 1954 to 1962. Seismicity and focal mechanisms support the hypothesis of spreading by ocean-ridge–transform-fault mechanism.

*beneath island arcs.* The gross structure of an idealized island arc as shown in Figure 1 is based on the results of *Oliver and Isacks* [1967]. Their study was primarily concerned with the Fiji-Tonga area. Comparison of seismic waves generated by deep earthquakes in the seismic zone and propagated along two different kinds of paths, one along the seismic zone and one through an aseismic part of the mantle, demonstrated the existence of an anomalous zone in the upper mantle. The anomalous zone was estimated to be about 100 km thick and to be bounded on the upper surface by the seismic zone. Thus, the zone dips beneath the Tonga arc at about 45° and extends to depths of almost 700 km. The zone is anomalous in that attenuation of seismic waves is low and seismic velocities are high relative to those of the mantle at comparable depths elsewhere. Recent studies of the Japanese arc [*Wadati et al.*, 1967; *Utsu*, 1967] have confirmed the existence of such a structure for that region. Similar zones appear to be associated with other island arcs [*Oliver and Isacks*, 1967; *Cleary*, 1967; *Molnar and Oliver*, 1968].

The presence of a high-velocity slab beneath an island arc introduces a significant azimuthal variation in the travel times of seismic waves. Such variations with respect to source anomalies are shown by *Herrin and Taggart* [1966], *Sykes* [1966], *Cleary* [1967] and are indicated by the data of *Carder et al.* [1967] all for the case of the Longshot nuclear explosion. With respect to station anomalies such variations are shown by *Oliver and Isacks* [1967], *Utsu* [1967], *Cleary and Hales* [1966], and *Herrin* [1966] from data from earthquakes. These effects must therefore be taken into account as sources of systematic errors in the locations of earthquakes and the construction of travel-time curves. The large anomaly of $Q$ associated with the slab must play a very important role in the $Q$ structure of the mantle, especially for studies based on body waves from deep earthquakes. Studies in which this effect is ignored [e.g., *Teng*, 1968] must be reassessed on this basis.

Oliver and Isacks associated the anomalous zone with the layer of low attenuation near the surface to the east of Tonga. In their interpretation of the data, they correlated low attenuation with strength to arrive at the structure of Figure 1 in which the lithosphere, a layer of strength, descends into the mantle. This configuration suggests the mobility of the lithosphere implied in Figure 1 and described in the introduction. Based on current estimates of lithosphere velocities and other parameters, the down-going slab would be much cooler than its surroundings for a long time interval. Although there is little evidence supporting a direct relation between low attenuation and strength, an indirect relation based on the dependence of each parameter on temperature is reasonable. This point is discussed further in another section.

*Bending of lithosphere beneath an island arc.* The evidence supporting the model in which the lithosphere plunges beneath the island arc is varied. To explore this point further, consider first the configuration of the upper part of the lithosphere in the vicinity of an island arc (Figure 7*a*). Seismic refraction studies of a number of island arcs have been made. Invariably they show the surface of the mantle, which is shallow beneath the deep ocean, deepening beneath the trench, as suggested by Figure 7*a*. Although some authors suggest that the mantle merely deepens slightly beneath the islands of the arc and shoals again behind the arc, evidence for such a structure is incomplete. Mantle velocities beneath the islands, where determined, are low, and there is no case for which the data could not be interpreted as suggested in Figure 7*a* (see, e.g., *Badgley* [1965] and *Officer et al.* [1959]). In fact, the difficulty experienced in documenting the model in which the mantle is merely warped beneath the islands is evidence against this model. The main crustal layer as determined from seismic refraction studies seems to parallel the surface of the dipping mantle beneath the seaward slope of the trench. In some interpretations the crustal layer thins beneath the trench; in others it thickens or remains constant. Perhaps these are real variations from trench to trench, but the data are not always definitive.

Thinning of the crust has been interpreted by *Worzel* [1965] and others as an indication of extension, and there is considerable evidence in the structure of the sediments on the seaward slopes of many trenches supporting the hypothesis of extension (see, e.g., *Ludwig et al.* [1966]). Figure 8, one of Ludwig's sections across the Japan trench, demonstrates this point dramatically. Several graben-like structures are seen on the seaward slope of the trench. Although such evidence for extension has been cited as an argument against sea-floor spreading and convection on the basis that down-going currents at the sites of the ocean deeps would cause compression normal to the arcs, the argument loses its force when the role of the lithosphere is recognized. All the evidence for extension relates only to the sediments and crust, i.e.,

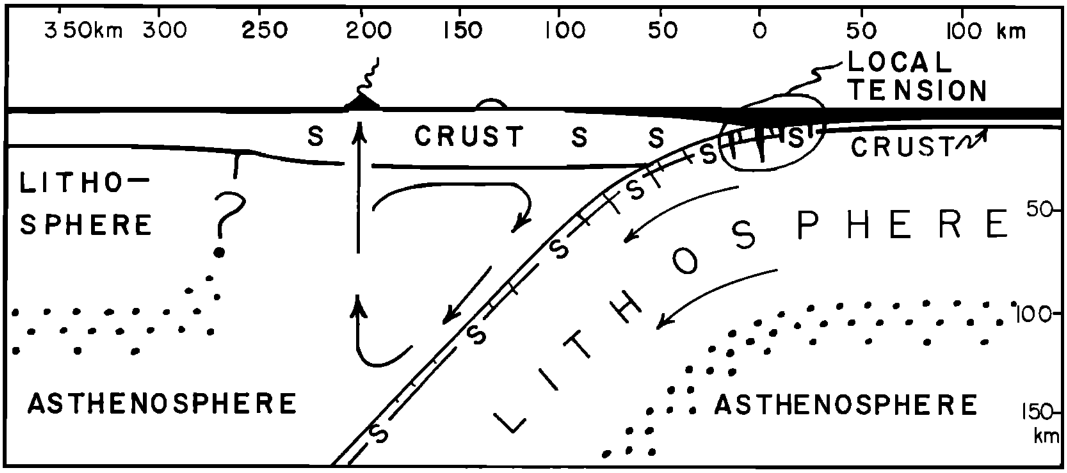



Fig. 7*a*.

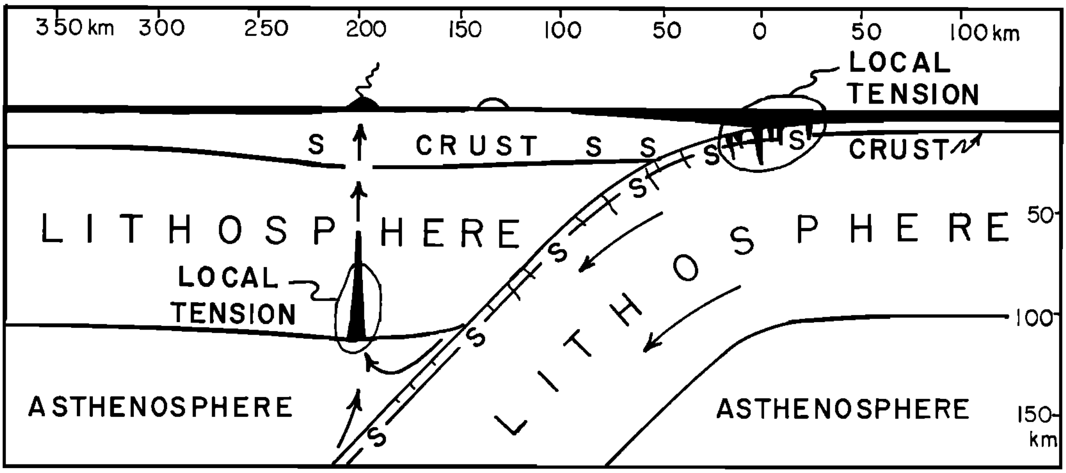



Fig. 7*b*.

Figure 7 shows vertical sections through an island arc indicating hypothetical structures and other features. Both sections show down-going slab of lithosphere, seismic zone near surface of slab and in adjacent crust, tensional features beneath ocean deep where slab bends abruptly and surface is free. (In both sections, *S* indicates seismic activity.) (*a*) A gap in mantle portion of lithosphere beneath island arc and circulation in mantle associated with crustal material of the slab and with adjoining mantle [*Holmes*, 1965]. (*b*) The overriding lithosphere in contact with the down-going slab and bent upward as a result of overthrusting. The relation of the bending to the volcanoes follows *Gunn* [1947]. No vertical exaggeration.

the upper few kilometers of the lithosphere. For the models pictured in Figure 7 in which a thick strong layer bends sharply as it passes beneath the trench, extensional stresses are predicted near the surface on the convex side of the bend even though the principal stress deeper in the lithosphere may be compressional. Earthquake activity beneath the seaward slope of the trench is, in general, infrequent and apparently of shallow depth. The focal mechanisms that have been determined for such shocks indeed indicate extension as predicted, i.e. normal to the trench, the axis of bending (*Stauder* [1968] and T. Fitch and P. Davis, personal communi-

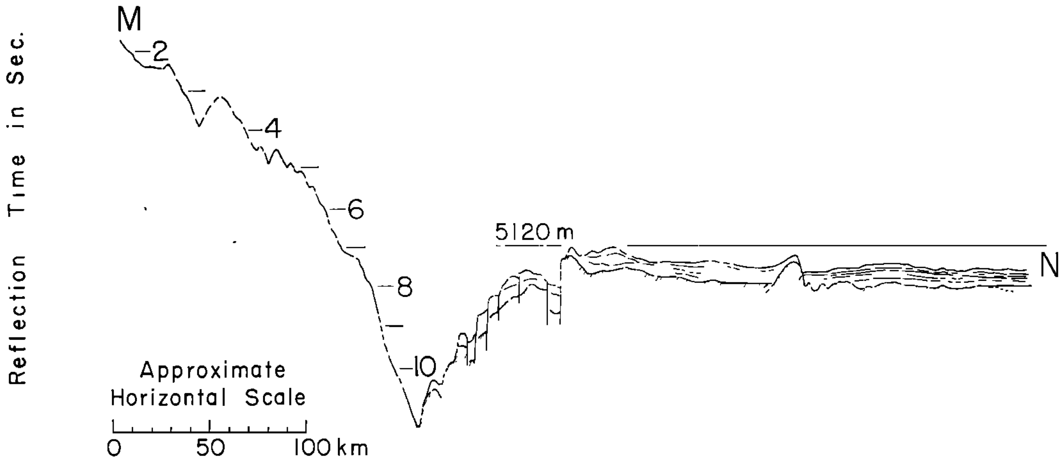



Fig. 8. Seismic reflection profile across the Japan trench extending easterly along 35°N from point M near Japan to point N [after *Ludwig et al.*, 1966]. Vertical scale represents two-way reflection time in seconds (i.e., 1 sec = 1 km of penetration for a velocity of 2 km/sec). Note block faulting along seaward slope of trench demonstrating extension in crust and inclusion of sediments in basement rocks. Also note shoaling of oceanic basement on approaching trench as suggested by work of *Gunn* [1937]. Vertical exaggeration ~25 : 1.

cations). Stauder demonstrates this point very well in a paper on focal mechanisms of shocks of the Aleutian arc.

The extensional features also suggest a mechanism for including and transporting some sediments within the down-going rock layers. As implied by Figure 7*a*, sediments in the graben-like features may be carried down to some depth in quantities that may be very significant petrologically, as suggested by *Coats* [1962]. Probably not all the sediments carried into the trench by motion of the sea floor or by normal processes of sedimentation are absorbed in the mantle, however. There are large volumes of low-density material beneath the inner slope on the island side of most trenches [*Talwani and Hayes*, 1967] that may correspond to sediment scraped from the crust and deformed in the thrusting. Unfortunately, the structure of these low-density bodies is not well explored, and, in fact, the very difficulty of exploring them may be an indication of their contorted nature, which results from great deformation.

The above arguments apply to trenches that are relatively free of flat-lying sediments, such as the Japan or Tonga trenches. The occurrence of substantial quantities of flat-lying undeformed sediments in some other trenches has been cited as evidence against underthrusting in island arcs [*Scholl et al.*, 1968]. Accumulation of underformed sediments depends on the ratio of rate of sediment accumulation to rate and continuity of underthrusting, and such data must be evaluated for each area with these factors in mind. The South Chile trench, for example, has a large sedimentation rate but no associated deep earthquakes, suggesting little or no recent thrusting. The results of Scholl et al. must be considered in this light. The Hikurangi trench (east of northern New Zealand), another example of a partially filled trench, is also thought to be in a zone of low convergence rate (see *Le Pichon* [1968] and Figure 2).

*Underthrusting beneath island arcs.* The shallow earthquakes mentioned above that indicate extension normal to the arc occur relatively infrequently and appear always to be located beneath or seaward of the trench axis. The earthquakes that account for most of the seismic activity at shallow depths in island arcs are located beneath the landward slope of the trench and form a slab-like zone that dips beneath the island arc [*Fedotov et al.*, 1963, 1964; *Sykes*, 1966; *Hamilton*, 1968; *Mitronovas et al.*, 1968]. This point is illustrated in Figure 9, which shows a vertical section through the Tonga arc. Note that, for a wide range of depths, foci are confined to a zone 20 km or less in thickness.

In the focal mechanisms of the shallow

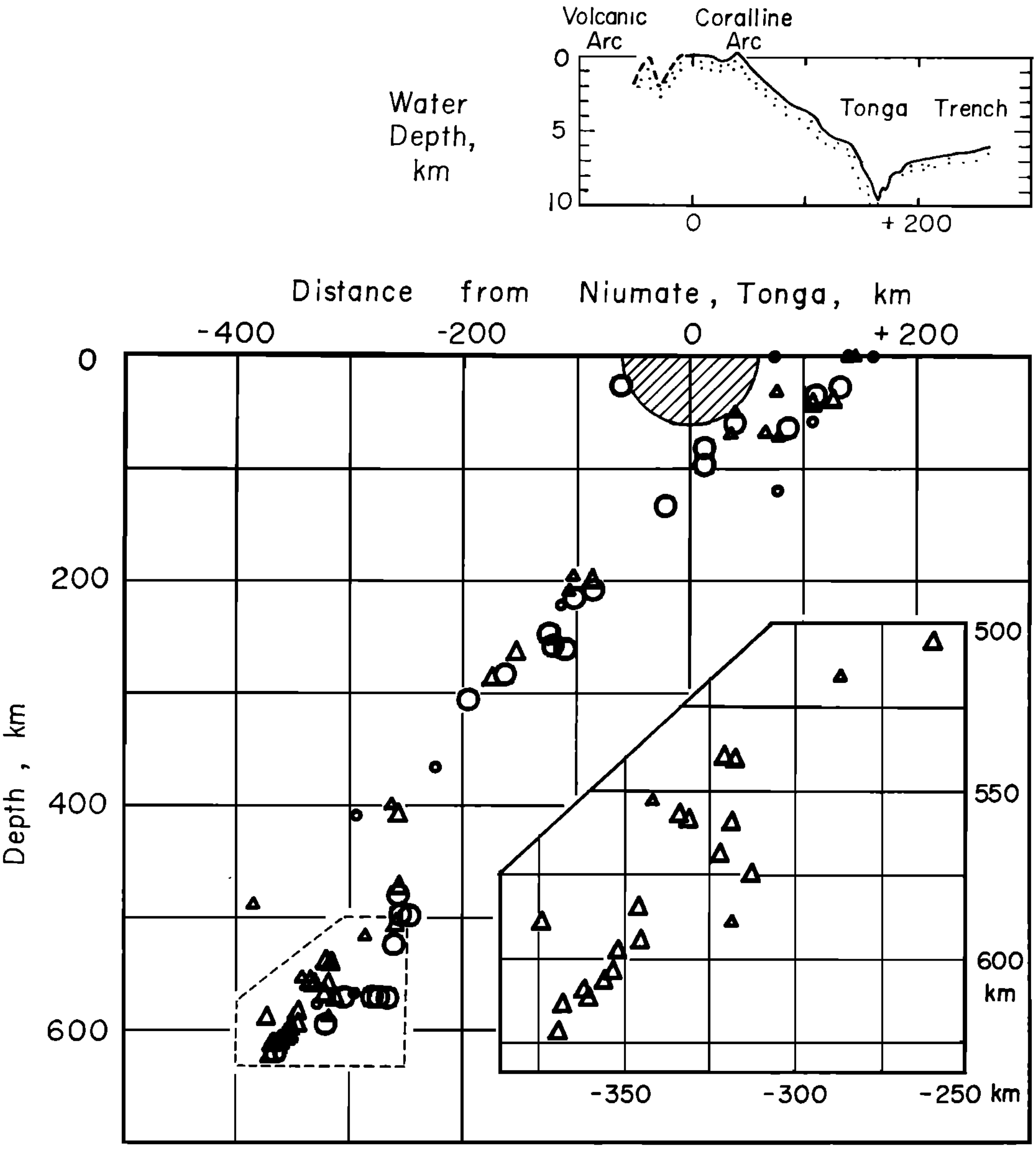



Fig. 9. Vertical section oriented perpendicular to the Tonga arc. Circles represent earthquakes projected from within 0 to 150 km north of the section; triangles correspond to events projected from within 0 to 150 km south of the section. All shocks occurred during 1965 while the Lamont network of stations in Tonga and Fiji was in operation. Locations are based on data from these stations and from more distant stations. No microearthquakes from a sample of 750 events originated from within the hatched region near the station at Niumate, Tonga (i.e., for *S-P* times less than 6.5 sec). A vertical exaggeration of about 13:1 was used for the insert showing the topography [after *Raitt et al.*, 1955]; the horizontal and vertical scales are equal in the cross section depicting earthquake locations. Lower insert shows enlargement of southern half of section for depths between 500 and 625 km. Note small thickness (less than ~20 km) of seismic zone for wide range of depths.

shocks along the slab-like zone of the Tonga-Kermadec arc, *Isacks and Sykes* [1968] find consistent evidence for underthrusting of the seaward block beneath the landward block. Abundant evidence for a similar process for various island arcs of the North Pacific is found by *Stauder* [1962, 1968], *Udias and Stauder* [1964], *Stauder and Bollinger* [1964, 1966*a*, *b*], *Aki* [1966], and *Ichikawa* [1966]. Critical evaluation of focal mechanism data by *Adams* [1963], *Hodgson and Stevens* [1964], *Stauder* [1964], and *Ritsema* [1964] shows that the generalization that strike-slip faulting is predominant in island arcs is based on unreliable data and possible systematic errors in the analyses. The recent data, greatly improved in quality and quantity, indicate that, in fact, dip-slip mechanisms are predominant in island arcs. The thrust fault mechanisms characteristic of shallow earthquakes in island arcs thus appear to reflect directly the relative movements of the converging plates of lithosphere and the downward motion of the oceanic plate. The compatibility of these motions as determined by focal mechanism data with the worldwide pattern of plate movements is discussed later and is shown to be excellent.

Considerable evidence for underthrusting in the main shallow seismic zone exists in other kinds of observations. Geodetic and geologic studies of the Alaskan earthquake of 1964 [*Parkin*, 1966; *Plafker*, 1965] strongly support the concept of underthrusting. Geologic evidence also indicates the repeated occurrence of such thrusting in this arc during recent time [*Plafker and Rubin*, 1967]. Data from other arcs on crustal movements are voluminous and have not all been examined in light of the hypotheses of the new global tectonics. In fact, in many arcs the principal zone of underthrusting would outcrop beneath the sea and important data would be largely obscured. One important point can be made. It is well known [*Richter*, 1958] that vertical movements in island arcs are of primary importance. This contrasts with the predominantly horizontal movement in such zones as California, where strike-slip faulting predominates.

*Other shallow activity in island arcs.* In some island arcs there is appreciable shallow seismic activity landward of the principal seismic zone. This activity, which is distinct from that of the deep seismic zone below it, appears to be confined mainly to the crust and to be secondary to the activity along the main seismic zone. The Niigata earthquake of June 16, 1964, appears to be located in such a secondary zone of the North Honshu arc. The mechanism of this earthquake [*Hirasawa*, 1965] indicates that the axis of maximum compressive stress is more nearly horizontal than vertical and trends perpendicular to the strike of the North Honshu arc. It is interesting that this stress is also perpendicular to the trend of Neogene folding in North Honshu [*Matsuda et al.*, 1967]. These results might indicate some compressive deformation of the overriding plates in the models of Figure 7.

*Deep earthquakes: the down-going slab.* The shallow seismic zone indicated by the major seismic activity is continuous with the deep zone, which normally dips beneath the island arc at about 45°. The thickness of the seismic zone is not well known in most cases, but it appears to be less than about 100 km and some evidence suggests that it may, at least in some areas, be less than 20 km. Figure 9 illustrates this point for a section through the Tonga arc. Although the surface approximating the distribution of hypocenters may be described roughly as above, it is clear that significant variations from this simple picture exist and are important. For example, the over-all dips may vary from at least 30° to 70°, and locally the variation may be greater, as suggested by the data in Figure 9. For the Tonga-Kermadec arc, the number of deep events is large and the zone can be defined in some detail [*Sykes*, 1966]. Sykes was able to show, as a result of a marked curvature of the northern part of the Tonga arc, a clear correlation between the configuration of the deep seismic zone and surface features of the arc, thereby demonstrating the intimate relationship between the deep and the shallow processes.

For most arcs, however, the number of deep events, particularly since the World-Wide Standardized Seismograph Network has been in operation, is relatively small; therefore, the deep zones cannot be defined as precisely as one might desire. Nevertheless, sufficient information is available on the pattern of seismic activity so that the concept of the mobile lithosphere can be tested in general, and it must be assumed that subsequent detailed studies of other island arcs may reveal contortions in the seismic zone comparable with the contortions already found in Tonga-Fiji.

*Focal mechanisms.* The simple underthrusting typical of the shallow earthquakes of the principal zones does not, in general, persist at great depths. For shocks deeper than about 100 km the orientation of the focal mechanisms varies considerably but exhibits certain clear-cut regularities. To understand these regularities, it is important to recall what is determined in a focal mechanism solution. The double-couple solution, which appears to be the best representation of most earthquakes, comprises two orthogonal nodal planes, either of which may be taken as the slip plane of the equivalent shear dislocation. Bisecting these nodal planes are the axis of compression, $P$, in the quadrants of dilatational first motions and the axis of tension, $T$, in the quadrants of compressional first motions. The axis formed by the intersection of the nodal planes is the null, or $B$, axis parallel to which no relative motion takes place. If one nodal plane is chosen as the slip plane, the pole of the other nodal plane is the direction of relative motion of the *slip vector*. It is important to realize that the primary information given by a double-couple solution is the orientation of the two possible slip planes and slip vectors. The interpretation of the double-couple mechanisms in terms of stress in the source region requires an assumption about the failure process. The $P$, $T$, and $B$ axes correspond to the maximum, minimum, and intermediate axes of compressive stress in the medium *only* if the shear dislocation is assumed to form parallel to a plane of maximum shear stress in the medium, i.e., a plane that is parallel to the axis of intermediate stress and that forms a 45° angle to the axes of maximum and minimum stress.

*Patterns of focal mechanisms for deep earthquakes.* The most striking regularity in the orientation of the double-couple focal mechanisms of deep and intermediate earthquakes is the tendency of the $P$ axes to parallel the local dip of the seismic zone. Figure 10 illustrates this point for the three zones (Tonga, Izu-Bonin, and North Honshu) for which reliable data are most numerous. This figure also shows that, although the orientation of the axes of tension and the null axes tend to be less stable than the compressional axes, these axes are not randomly oriented. The axis of tension tends to be perpendicular to the seismic zone; the null axis, parallel to the strike of the zone. These generalizations are shown schematically in Figure 11. The slip planes and slip directions are thus systematically *nonparallel* to the seismic zones; the orientations are therefore difficult to reconcile with a simple shearing parallel to the seismic zone as suggested by the common concept of the zone as a large thrust fault. *Sugimura and Uyeda* [1967] sought to reconcile the observations with that concept by postulating a reorientation of crystalline slip planes perpendicular to the axis of maximum compressive stress, such that in the case of horizontal compression the slip planes would tend to be vertical.

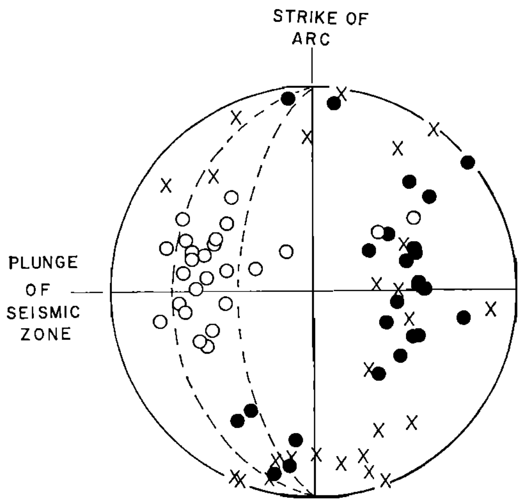



Fig. 10. Orientations of the axes of stress as given by the double-couple focal mechanism solutions of deep and intermediate earthquakes in the Tonga arc, the Izu-Bonin arc, and the North Honshu arc. Open circles are axes of compression, $P$; solid circles are axes of tension, $T$; and crosses are null axes, $B$, all plotted on the lower hemisphere of an equal-area projection. The data, selected from available literature as the most reliable solutions, are taken from *Isacks and Sykes* [1968], *Honda et al.* [1956], *Ritsema* [1965], and *Hirasawa* [1966]. The data for each of the three arcs are plotted relative to the strike of the arc (Tonga arc, N 20°E; Izu-Bonin, N 15°W; North Honshu arc, N 20°E). The dips of the zones vary between about 30° and 60°, as indicated by the dashed lines in the figure. Note the tendency of the $P$ axes to parallel the dip of the seismic zone and the weaker tendency for the $T$ axes to be perpendicular to the zone.

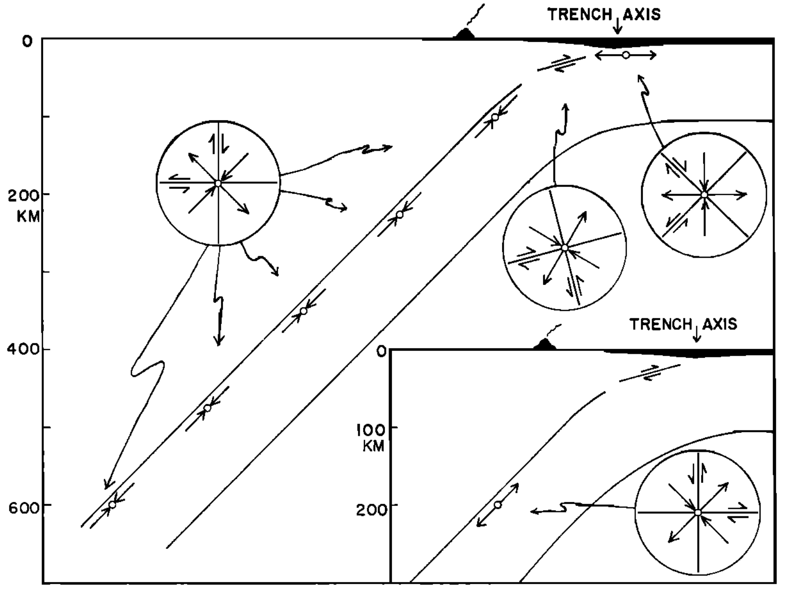



Fig. 11. Vertical sections perpendicular to the strike of an island arc showing schematically typical orientations of double-couple focal mechanisms. The horizontal scale is the same as the vertical scale. The axis of compression is represented by a converging pair of arrows; the axis of tension is represented by a diverging pair; the null axis is perpendicular to the section. In the circular blowups, the sense of motion is shown for both of the two possible slip planes. The features shown in the main part of the figure are based on results from the Tonga arc and the arcs of the North Pacific. The insert shows the orientation of a focal mechanism that could indicate extension instead of compression parallel to the dip of the zone.

Alternatively, *Isacks and Sykes* [1968] show that, if it is assumed that the slip planes form at angles with respect to the axis of maximum compressive stress that are not significantly different from 45°, then a very simple interpretation can be made on the basis of the model of Figure 1. In this interpretation the axis of maximum compressive stress is parallel to the dip of the seismic zone (i.e., parallel to the presumed motion of the slab in the mantle), and the axis of least compressive stress is perpendicular to the zone or parallel to the thin dimension of the slab.

The tendency for the compressive axes to be more stable than the other two axes can be interpreted to indicate that the difference between the intermediate and the least principal stresses is less than the difference between the greatest and the intermediate principal stresses. In general, the stress state may be quite variable owing to contortions of the slab, as suggested by Figure 9. Possibly large variability in the orientations of the deep mechanisms would, therefore, be expected, especially near parts of the zone with complex structure.

The important feature of the interpretation presented here is that the deep earthquake mechanisms reflect stresses in the relatively strong slab of lithosphere and do not directly accommodate the shearing motions parallel to the motion of the slab as is implied by the simple fault-zone model. The shearing deformations parallel to the motion of the slab are presumably accommodated by flow or creep in the adjoining ductile parts of the mantle.

Do the stresses in the slab vary with depth? In particular, the axis of least compressive stress, the $T$ axis, may be parallel to the dip of the zone if the material at greater depths were sinking and *pulling* shallower parts of the slab [*Elsasser*, 1967]. In the Tonga, Aleutian, and Japanese arcs, the focal mechanisms indicate that the slab is under compression parallel to its dip at all depths greater than about 75 to 100 km. In these arcs, therefore, any extension in the slab must be shallower than 75 to 100 km.

Very limited evidence from the Kermadec [*Isacks and Sykes*, 1968], New Zealand (North Island) [*Adams*, 1963], South American (A. R. Ritsema, personal communication), and Sunda (T. Fitch, personal communication) arcs suggests, however, that mechanisms indicating extension of the slab, as shown in the insert of Figure 11, may exist at intermediate depths in some arcs. Further work is required to distinguish such mechanisms from the underthrusting type of mechanism characteristic of earthquakes at shallow depths or from complex mechanisms related to changes in structure or contortions of the slab.

*Process of deep earthquakes.* The idea that deep earthquakes occur in downgoing slabs of lithosphere has important implications for the problem of identifying the physical process responsible for sudden shear failure in the environment of the upper mantle. That deep earthquakes are essentially sudden shearing movements and not explosive or implosive changes in volume is now extensively documented (see *Isacks and Sykes* [1968] for references). Anomalous temperatures and composition might be expected to be associated with the down-going slab, either or both of which may account for the existence of earthquakes at great depths.

Several investigators [*Raleigh and Paterson*, 1965; *Raleigh*, 1967] concluded that dehydration of hydrous minerals can release enough water to permit shear fracture at temperatures between about 300° and 1000°C. Although *Griggs* [1966] and *Griggs and Baker* [1968], assuming normal thermal gradients, suggested that these reactions would not take place for depths greater than about 100 km, rates of underthrusting as high as 5 to 15 cm/yr suggest that temperatures low enough to permit these reactions to occur may exist even to depths of 700 km. Certainly a re-evaluation of these processes is in order.

The lowest temperatures, the largest temperature gradients, and the largest compositional anomalies would probably be most marked near the upper part of the slab, i.e. the part corresponding to the crust and uppermost mantle in the surficial lithosphere. Thus, the seismic activity associated with these anomalies might be expected to concentrate near the upper part of the slab, as is suggested in Figures 7*a* and 11 and supported by the data shown in Figure 9. Although catastrophic phase changes may be ruled out as direct sources of seismic waves on the basis of the radiation pattern of the waves, the possibility remains that the stresses responsible or partly responsible for shear failure may result from somewhat slower phase changes.

*Seismic activity versus depth.* Frequencies of earthquakes versus depth for several island arcs are shown in Figure 12. There are two main results emerging from these analyses. (1) In all island arcs studied the activity decreases in the upper 100 to 200 km approximately exponentially as a function of depth with a decay constant of about 100 km [*Sykes*, 1966]. (2) At greater depths the seismic activity in many (but not all) island arcs increases relative to the exponential decay extrapolated from shallower depths, and the seismic activity shows a fairly well-defined maximum in some depth range in the upper mantle. The variation of seismic activity with depth is thus grossly correlated with the variation of seismic focal mechanisms with depth and supports the generalization that deep earthquake mechanisms have a different relationship to the zone than shallow mechanisms do. In this correlation the earthquakes that define the shallow exponential decay in seismic activity are characterized by the underthrusting type mechanisms, whereas the deeper earthquakes appear to be related to the stresses in the down-going slab.

There is an approximate correlation of the decrease in seismic activity versus depth with a similar general decrease in seismic velocities, $Q$, and viscosity in the upper 150 km. These effects may be related to a decrease in the difference between the temperature and local melting temperature. Thus, the decrease in activity with depth may correspond to an increase in the ratio of the amount of deformation by ductile flow to that by sudden shear failure. An implication of this interpretation is that the exponential decay constant of 100 km may roughly indicate the thickness of the overthrust plate of lithosphere. This interpretation is illustrated in Figure 7*b*, in which the overriding plate of lithosphere is in 'contact' with the down-going plate along the seismic zone. As shown in a later section, the assumption that the depth distribution of shallow earthquakes

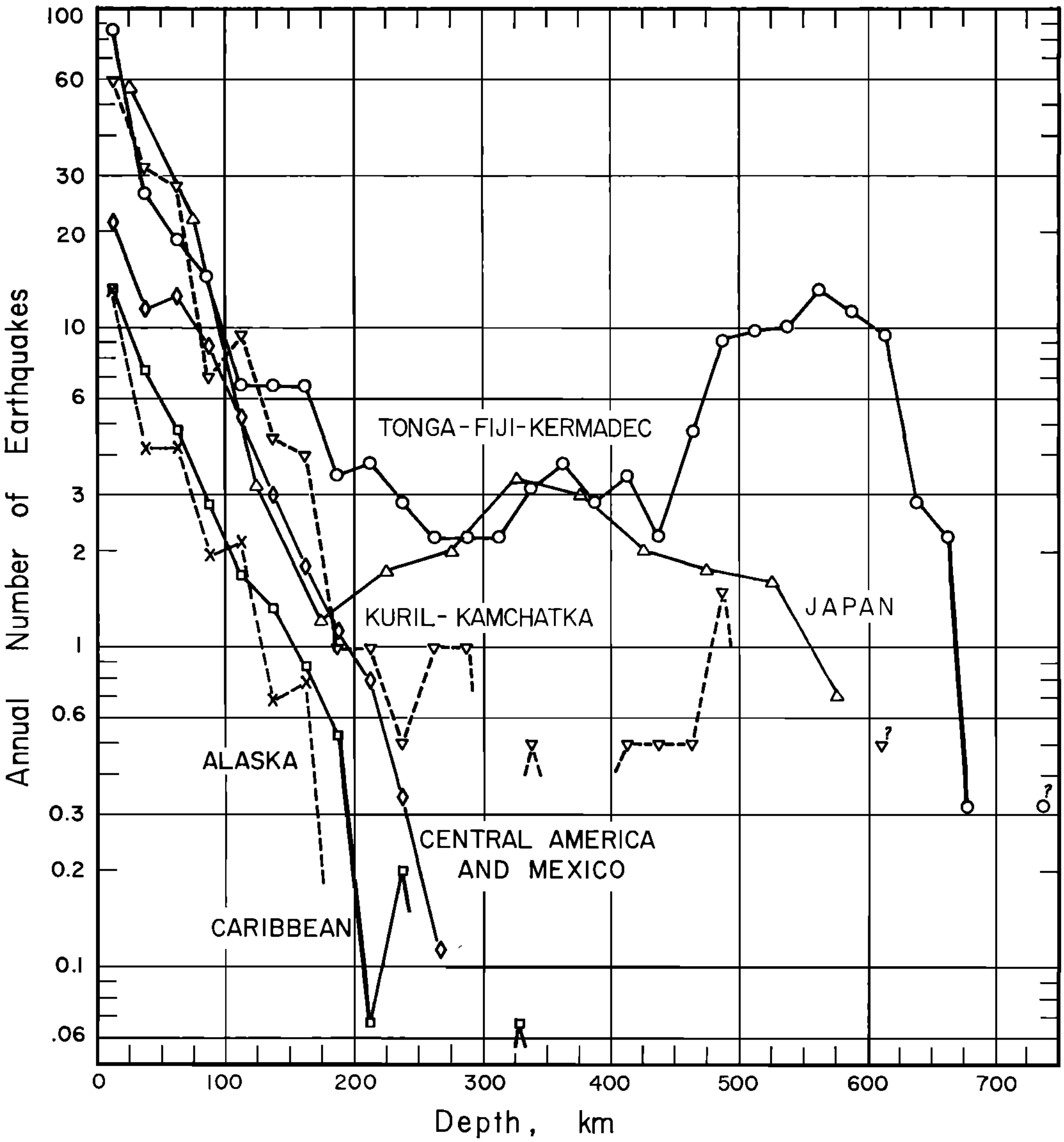



Fig. 12. Number of earthquakes per 25-km depth intervals as function of depth for several island arcs. Except for Japan, data are from *Sykes* [1966]. Data for Japan expressed as percentage of events per 50-km depth intervals [*Katsumata*, 1967]. Since the various curves were not normalized for the sample lengths and for the lower limit of detectability in each area, only the relative shapes and not the absolute levels of the various curves should be compared with one another. The number of earthquakes per unit depth within the upper 200 km of all these island arcs is approximately proportional to exp $(-Z/100)$, where $Z$ is the depth in kilometers. Peaks in activity below 200 km appear to fluctuate both in amplitude and in depth among the various arcs.

of the mid-ocean rift system yields a measure of the thickness of the lithosphere is not an unreasonable one.

Several lines of evidence do not, however, support the existence of thick lithosphere directly beneath and behind the arc as shown in Figure 7*b*. *Oliver and Isacks* [1967] and *Molnar and Oliver* [1968] show that high-frequency $S_n$ does not propagate across the concave side of island arcs, which probably indicates that the uppermost mantle there has low $Q$ values. This result is in agreement with the low $P_n$ velocities generally found beneath islands of many arcs. Also, the active volcanism and high heat flow characetristic of the concave side of island arcs [*Uyeda and Horai*, 1964; *Sclater et al.*, 1968] suggest that the lithosphere may be thin there. These data are qualitatively fitted by the model shown in Figure 7*a*. One implication of this figure is that at least part of the shallow earthquake zone might not result from the contact between two pieces of lithosphere but might instead indicate an embrittled and weakened zone formed by the downward moving crustal materials [*Raleigh and Paterson*, 1965; *Griggs*, 1967]. In this case the exponential decay in activity might reflect changes in the properties of the earthquake zone as a function of depth. Thus, both models in Figure 7 must be retained for the present.

Although in some arcs such as the Aleutians or Middle America the exponential decay in activity appears to be the only feature present in curves of activity versus depth, most arcs exhibit a more or less well-defined maximum in activity in the mantle, as illustrated in Figure 12. The approximate ranges of depth of these maxima are shown in Figure 13 for several island arcs. The main point of this figure is to show that the depths of these maxima vary considerably among the various arcs and do not appear to be associated with any particular level of depth in the mantle, contrary to general opinion. As shown in Figure 13, the depths of the deep maxima are approximately correlated with the rates of convergence in the arcs as calculated by Le Pichon. As will be shown later (see Figure 16), the correlation is considerably better between the rate of convergence and the *length* of the zone measured along the dip of the zone. Thus, the simplest explanation, one direct consequence of the model of Figure 1, is that the deep maxima are near the leading parts of the down-going slabs.

Two features of the distributions shown in Figures 12 and 13 may be related to certain levels of depth in the mantle. Although the length of the seismic zone measured along the dip of the zone exceeds 1000 km for several cases, no earthquakes with depths greater than 720 km have ever been documented. The U. S. Coast and Geodetic Survey (USCGS) has located no earthquakes with a depth greater than 690 km during the period 1961–1967. These depths are near the region of the mantle in which gradients in the variation of seismic velocities may be high [*Johnson*, 1967]. *Anderson* [1967*a*] argues that this region corresponds to a phase change in the material. These depths may therefore be in some way related to the boundary of the mesosphere as shown in Figures 1 and 14 and as discussed in the next section. The second feature is the absence of maxima around 300 km. Thus, in a worldwide composite plot of activity versus depth, a minimum in activity near this depth generally appears.

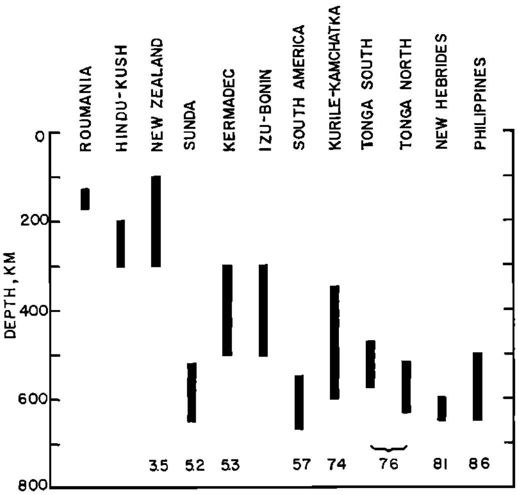



Fig. 13. Depth range of maxima in the seismic activity (numbers of earthquakes) as a function of depth in island arcs and arc-like structures for which data are sufficiently numerous. The data are from *Gutenberg and Richter* [1954], *Katsumata* [1967], *Sykes* [1966], and listings of earthquakes located by the USCGS in the preliminary determination of epicenters (PDE). The numbers at the bottom of the figure give the rate (in centimeters per year) of convergence for the arc as plotted in Figure 2. Note that the maxima occur over a wide range of depths and that the depths appear to correlate, in general, with the calculated slip rate.

*Downward movement of lithosphere in the mantle: some hypotheses.* Although the concept is so new that it is difficult to make definitive statements, a brief speculative discussion is in order to emphasize the importance of these results in global tectonics. Figure 14, four hypothetical and very schematic cross sec-

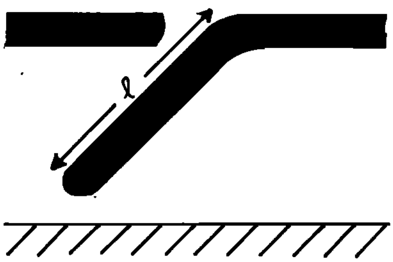


Fig. 14*a*. Length $l$ is a measure of the amount of underthrusting during the most recent period of sea-floor spreading.

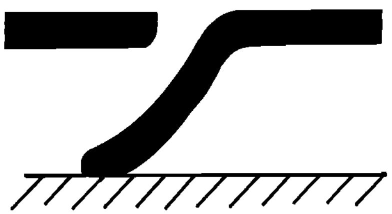


Fig. 14*b*. Lithosphere is deformed along its lower edge as it encounters a more resistant layer (the mesosphere).

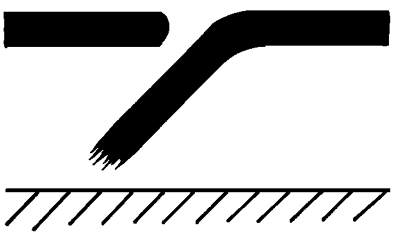


Fig. 14*c*. Length of seismic zone is the product of rate of underthrusting and time constant for assimilation of slab by upper mantle.

Fig. 14*d*. A piece (or pieces) of the lithosphere becomes detached either by gravitational sinking or by forces in the asthenosphere.

Figure 14 shows four possible configurations of an underthrust plate of lithosphere in island arcs. Solid areas indicates lithosphere; white area, asthenosphere; hatched area, mesosphere.

tions of an island arc, illustrates some points that should be considered.

Figure 14*a* shows a case in which the lithosphere has descended into the mantle beneath an island arc. In this model the lithosphere has not been appreciably modified with regard to its potential for earthquakes and the length of the submerged portion, $l$, and hence the depths of the deepest earthquakes are dependent on the rate of movement down dip and the duration of the current cycle of sea-floor spreading and underthrusting.

In Figure 14*b* the leading edge of the descending lithosphere has encountered significant resistance to further descent and has become distorted. In this situation, the depth of the deepest earthquakes in such a zone depends on the depth to the mesosphere. *Sykes'* [1966] analysis of the relocations of earthquakes in the Tonga arc (see also Figure 9) reveals the presence of contortions of the lower part of the seismic zone which might indicate a phenomenon similar to that pictured in Figure 14*b*. This model has the interesting consequence that a cycle of sea-floor spreading might be terminated or sharply modified by the bottoming of the lithosphere at certain points.

Figure 14*c* indicates schematically that the depths of the deepest earthquakes might depend on modification of the lithosphere by its environment. In this model the depth of the deepest shocks depends on the rate of descent and the rate of modifications or absorption of the lithosphere.

In Figure 14*d* the lower portion of the descending part of the lithosphere is not connected with the upper portion, possibly because it has pulled away as a result of a large density contrast between the sinking part of lithosphere and the surrounding mantle. Another possibility is that the lower piece represents a previous episode of movement, so that the break between the pieces then represents a period of quiescence in the surface movements. For example, the Spanish deep earthquake of 1954 [*Hodgson and Cock*, 1956] and the very deep earthquakes beneath the North Island of New Zealand [*Adams*, 1963] might indicate isolated pieces of lithosphere. A variant of Figure 14*d* is the case in which movements of the ductile material of the asthenosphere, movements that could be quite different from the movements of the surficial lithospheric plates, could deform the slabs and possibly break off pieces. For example, the marked contortions of the deep seismic zone of Tonga may be explained by such deformation. Thus, although the evidence is at present only suggestive, such evidence is important because of the implications of the hypotheses with regard to the dynamics of the system *within the asthenosphere.* Various combinations of the effects illustrated in Figure 14 may also be considered.

*Lateral terminations of island arcs.* The discussions above are based on, and apply largely to, the structure of an island arc taken in a vertical section normal to the strike of an arc. The three-dimensional configuration of the arc must also be considered. The plate model of tectonics provides, in a simple way, for the termination of an island arc by the abrupt or gradual transition to a transform fault, by a decrease in the rate of convergence to zero, or by some combination of these. In the first case the relative movement that is predominantly normal to the zone of deformation changes to relative movement that is predominantly parallel to the zone. In the second case the pole governing the relative motion between the plates may be located along the strike of the feature. *Isacks and Sykes* [1968] describe what may be a particularly simple case of the first possibility. The northern end of the Tonga arc appears to end in a transform fault that strikes approximately normal to the arc. In this case evidence is also found for a scissors type of faulting in which the downgoing Pacific plate tears away from the part of the plate remaining at the surface.

*Summary of data on island arcs.* The lithosphere model of an island arc thus gives a remarkably simple account of diverse and important observed features of island arcs. The existence and distribution of earthquakes in the mantle beneath island arcs, the anomalous transmission properties of deep seismic zones, and the correspondences in the variations of seismic activity and the orientations of the focal mechanisms as functions of depth are all in agreement with the concept of a cooler, relatively strong slab moving through a relatively ductile asthenosphere. The bend in the slab required by this movement provides a simple means of reconciling the conflicting evidence for extension and compressional features of island arcs. The results suggest that there are two basic types of focal mechanisms. The first type is apparently confined to shallow depths and directly accommodates, and therefore indicates the direction of, the movements between the plates of lithosphere. The second type indicates stress and deformation *within* a plate of lithosphere and includes, besides the deep and intermediate earthquake mechanisms, the normal-faulting mechanisms at shallow depths beneath the axis of the trench and, possibly, the shallow earthquake mechanisms located landward of the underthrust zone. The deep earthquake zones may provide the most direct source of information on the movement of material in the asthenosphere and on the basic question of the relative importance of the lithospheric and asthenospheric motions in driving the convective system. The global pattern of motions between the plates, derived in part from the shallow focal mechanism in island arcs, provides a severe test of the hypothesis of plate movements in general and provides in particular key evidence for the conclusion that island arcs are the major zones of convergence and downward movements of the lithospheric plates. This evidence, including observations of directions as well as rates of movement, is discussed in the next section.

## Compatibility of Movements on a Worldwide Scale

In this section deformations along the world rift system and along island arcs and major mountain belts are examined for their internal consistency and for their global compatibility. The major finding is that these displacements can be approximated rather precisely by the interactions and the relative movements of large plates of lithosphere, much of the deformation being concentrated along the edges of the plates and relatively little deformation being within the individual plates themselves. It has long been recognized that recent deformations of the earth's surface are concentrated in narrow belts. These belts, which largely coincide with the major seismic zones of the world, include the world rift system, island arcs, and such island-arc-like features as active mountain belts and active continental margins. These major tectonic features do not end abruptly;

they appear to be linked together into a global tectonic scheme.

*Continuity of seismic belts and distribution of seismic activity.* Figure 15, a compilation of about 29,000 earthquake epicenters for the world as reported by the U. S. Coast and Geodetic Survey for the period 1961 to 1967 [*Barazangi and Dorman*, 1968], shows that most of the world's seismic activity is concentrated in rather narrow belts and that these belts may be regarded as continuous. Thus, if global tectonics can be modeled by the interaction of a few large plates of lithosphere, this model can account for most of the world's seismic activity as effects at or near the edges of the plates. Figure 15 also shows that the earthquakes occur much more frequently, in general, in the zones of convergence, the arcs and arc-like features, than in the zones of divergence, the ocean ridges. Along the ocean ridges, where the less complicated processes of tectonics are apparently occurring, the zones are narrow; on the continents, where the processes are apparently more complex, the zones are broad, and distinctive features are not easily resolved. Deep earthquake zones, indicated in Figure 15 only by the width of epicentral regions behind arcs, correspond to the zones of underthrusting. Thus, all the major features of the map of seismic epicenters are in general accord with the new global tectonics. No other hypothesis has ever begun to account so well for the distribution of seismic activity, which must rank as one of the primary observations of seismology. The details of the configuration of the seismic belts of Figure 15 are discussed further in other sections of this paper.

*Slip vectors.* Figure 3 illustrates the distribution of these major tectonic features and summarizes azimuths of motion as indicated by the slip vectors determined from various studies of the focal mechanisms of shallow-focus earthquakes. Deep and intermediate earthquakes as well as shallow earthquakes with normal faulting mechanisms near trenches were not represented in this figure, since these mechanisms are not thought to involve the relative displacements of two large blocks of lithosphere. Earthquake mechanisms were included in Figure 3 only when, by careful examination of the first-motion plots, we could verify that the slip vectors were reasonably well determined. These data were taken from *Stauder* [1962, 1968], *Stauder and Udias* [1963], *Stauder and Bollinger* [1964, 1966*a*, *b*], *Harding and Rinehart* [1966], *Ichikawa* [1966], *Sykes* [1967, 1968], *Banghar and Sykes* [1968], *Isacks and Sykes* [1968], and *Tobin and Sykes* [1968]. Although no attempt was made to ensure that the collection of mechanism solutions represented all the reliable previous work, nonetheless, the data are thought to be representative; no attempt was made to select the data by criteria other than their reliability. In some cases such as the aftershocks of the great Alaska earthquake of 1964 and the aftershocks of the large Rat Islands earthquake of 1965 [*Stauder and Bollinger*, 1966*b*; *Stauder*, 1968], only representative solutions were included, since the number of solutions for these regions was too large to depict clearly in Figure 3. Solutions cited as reliable by *Ritsema* [1964] as well as those of *Honda et al.* [1956], for example, were not used because they pertain to subcrustal shocks.

From each mechanism solution used one of two possible slip vectors was chosen as indicative of the relative motions of the two interacting blocks of lithosphere. For each slip vector the arrow depicts the relative motion of the block on which it is drawn with respect to the block on the other side of the tectonic feature. Since the double-couple model (or shear dislocation) appears to be an excellent approximation to the radiation field of earthquakes, it is not possible to choose from seismic data alone one of the two possible slip vectors as the actual motion vector (or alternatively to choose one of two possible nodal planes as the fault plane).

Nevertheless, the choice of one vector is not arbitrary but is justified either by the orientation of the vectors with respect to known tectonic features such as fracture zones or by the consistency of a set of vectors in a given region. For earthquakes located on such major transform faults as the oceanic fracture zones, the San Andreas fault, and the Queen Charlotte Islands fault (Figure 3), one of the slip vectors is very nearly parallel to the transform fault on which the earthquake was located. Observed surface breakage and geodetic measurements in some earthquakes, the alignment of epicenters along the strike of major transform faults, the linearity of fracture zones, and petrological evidence for intense shearing stresses in the

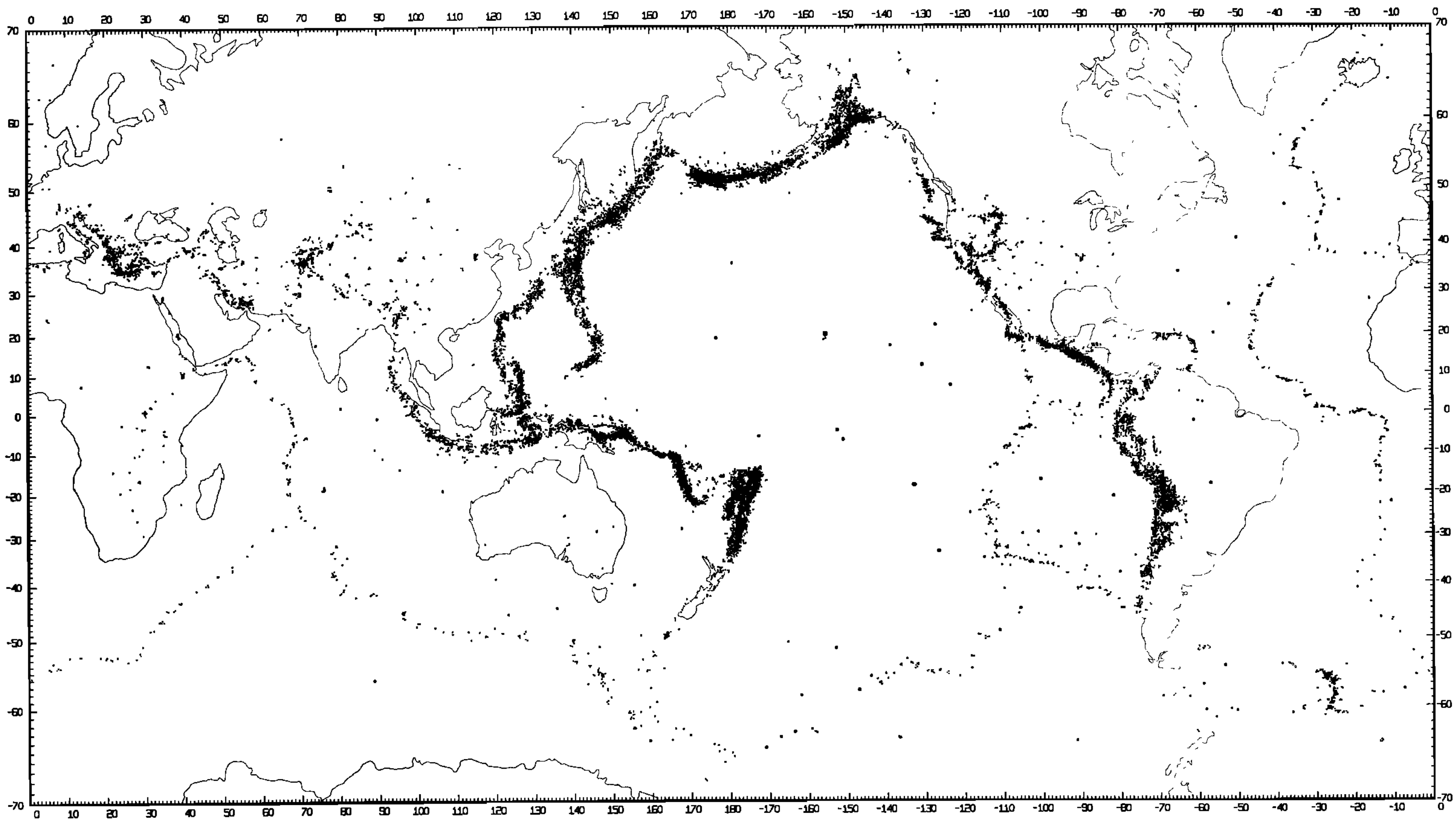



Fig. 15. Worldwide distribution of all earthquake epicenters for the period 1961 through 1967 as reported by U. S. Coast and Geodetic Survey [after *Barazangi and Dorman*, 1968]. Note continuous narrow major seismic belts that outline aseismic blocks; very narrow, sometimes steplike pattern of belts of only moderate activity along zones of spreading; broader very active belts along zones of convergence; diffuse pattern of moderate activity in certain continental zones.

vicinity of fracture zones constitute strong evidence for making a rational choice between the two possible slip vectors [*Sykes*, 1967]. The choice of the other possible slip vector (or nodal plane) for many of the oceanic fracture zones would indicate strike-slip motion nearly parallel to the ridge axis. On the contrary, earthquakes along the ridge crest but not on fracture zones do not contain a large strike-slip component but are characterized by a predominance of normal faulting.

*Evidence for motions of lithospheric plates.* One of the most obvious features in Figure 3 is that the slip vectors are consistent with the hypothesis that surface area is being created along the world rift system and is being destroyed in island arcs. Along the mid-Atlantic ridge, for example, slip vectors for more than ten events are nearly parallel to one another and are parallel to their neighboring fracture zones within the limits of uncertainty in either the mechanism solutions (about 20°) or the strikes of the fracture zones.

*Morgan* [1968] and *Le Pichon* [1968] showed that the distribution of fracture zones and the observed directions and rates of spreading on ocean ridges as determined from geomagnetic data could be explained by the relative motions of a few large plates of lithosphere. They determined the poles of rotation that describe the relative motion of adjacent plates on the globe. Our evidence from earthquake mechanisms and from the worldwide distribution of seismic activity is in remarkable agreement with their hypothesis. Although their data are mostly from ridges and transform faults, earthquake mechanisms give the relative motions along island arcs as well as along ridges and transform faults.

Le Pichon used data from ocean ridges to infer the direction of motion in island arcs. His predicted movements (Figure 2), which are based on the assumption of conservation of surface area and no deformation within the plates of lithosphere, compare very closely with mechanism solutions in a number of arcs. This agreement is a strong argument for the hypothesis that the amount of surface area that is destroyed in island arcs is approximately equal to the amount of new area that is created along the world rift system. Thus, although modest expansion or contraction of the earth is not ruled out in the new global tectonics, rapid expansion of the earth is not required to explain the large amounts of new materials added at the crests of the world rift system. This approximate equality of surface area is, however, probably maintained for periods longer than thousands to millions of years, but minor imbalances very likely could be maintained for shorter periods as strains within the plates of lithosphere. More exact knowledge of these imbalances could be of direct interest to the problem of earthquake prediction.

Figure 3 suggests that nearly all the east-west spreading along the East Pacific rise and the mid-Atlantic ridge is taken up either by the island arcs of the western Pacific or by the arc-like features bordering the west coasts of Central and South America. Much of the north-south spreading in the Indian Ocean is absorbed in the Alpide zone, which stretches from the Azores-Gibraltar ridge across the Mediterranean to southern Asia and then to Indonesia.

*Relative motions in the southwest Pacific.* Le Pichon's computed directions of motion in the Tonga and Kermadec arcs of the southwest Pacific agree very closely with mechanisms we obtained from a special study of that region [*Isacks and Sykes*, 1968]. Mechanisms south of New Zealand along the Macquarie ridge [*Sykes*, 1967; *Banghar and Sykes*, 1968] indicate a combination of thrust faulting and right-lateral strike-slip motion. These data suggest that the pole of rotation for these two large blocks is located about 10° farther south than estimated by *Le Pichon* [1968]. Although the Pacific plate is being *underthrust* in the Tonga and Kermadec arcs and in northern New Zealand, this plate is apparently being *overthrust* along the Macquarie ridge (see also *Summerhayes* [1967]). In this interpretation the Alpine fault is a right-lateral transform fault of the arc-arc type that connects two zones of thrusting with opposing dips. Computed slip vectors for this region also indicate a component of thrust faulting either along the Alpine fault itself or in other parts of the South Island of New Zealand. *Wellman*'s [1955] studies of Quaternary deformation, which indicate a thrusting component as well as a right-lateral strike-slip component of motion along the Alpine and associated faults, seem to be in general accord with this concept.

Likewise, the Philippine fault appears to connect a zone of underthrusting of the Pacific floor near the Philippine trench with a region of overthrusting west of the island of Luzon near the Manila trench. Also, the existence of a deep seismic zone in the New Hebrides arc that dips toward the Pacific rather than away from the Pacific as in the Tonga arc [*Sykes*, 1966] is understandable if the Pacific plate is being overthrust in the New Hebrides and underthrust in Tonga (Figure 1). The ends of these two arcs appear to be joined togther by one or more transform faults that pass close to Fiji, but additional complications appear to exist in this area.

*North Pacific.* The uniformity in the slip directions and the distribution of major faults along the margins of the North Pacific (with perhaps some systematic departure in the slip directions off the coast of Washington and Oregon) indicate that only two blocks are involved in the major tectonics [*Tobin and Sykes*, 1968; *Morgan*, 1968; *McKenzie and Parker*, 1967]. In this scheme, the San Andreas fault, the Queen Charlotte Islands fault, and a series of northwesterly striking faults in the Gulf of California are interpreted as major transform faults [*Wilson*, 1965*a*, *b*]. The observed rates of displacement along the San Andreas as determined geodetically [*Whitten*, 1955, 1956] are very similar to the rates determined from the seismicity by means of a dislocation model [*Brune*, 1968]. These rates are in close agreement with the rates inferred from magnetic anomalies for the region of growing ridges at the northwestern end of the San Andreas fault [*Vine and Wilson*, 1965; *Vine*, 1966]. Estimates of the total amount of offset along the San Andreas [*Hamilton and Meyers*, 1966] are comparable to the amount of offset needed to close the Gulf of California and to the width of the zones of northeasterly striking magnetic anomalies off the coast of Oregon and Washington [*Vine and Wilson*, 1965].

Thus, the present tectonics of much of the North Pacific can be related to the motion of the Pacific plate relative to North America and northeastern Asia. The slip vectors strike northwesterly along the west coast of the United States and Canada, represent nearly pure dip-slip motion in southern Alaska and the eastern Aleutians, and have an increasingly larger strike-slip component along the Aleutian arc as the longitude becomes more westerly. Displacements in the Kurile, Kamchatka, and Japanese arcs are nearly pure dip-slip and represent underthrusting of the Pacific plate beneath the arcs.

The system of great east–west fracture zones in the northeastern Pacific (Figure 2) apparently was formed more than 10 m.y. ago. Since that time the directions of spreading changed from east–west to their present northwest–southeast pattern [*Vine*, 1966]. The more westerly strike of the slip vectors along the Juan de Fuca and Gorda ridges is consistent with the hypothesis that the area to the east of these ridges represents a small separate plate [*Morgan*, 1968; *McKenzie and Parker*, 1967] that was underthrust beneath the coast of Washington and Oregon to form the volcanoes of the Cascade range. A few earthquakes that have been detected in western Oregon and Washington are apparently of a subcrustal origin [*Neumann*, 1959; *Tobin and Sykes*, 1968]. The tectonics of this block appears to be quite complex. Internal deformation within this block, as indicated by the presence of earthquakes [*Tobin and Sykes*, 1968], and the small number of subcrustal events previously mentioned suggest that the tectonic regime in this region is being readjusted.

*Depths of earthquakes, volcanism, and their correlation with high rates of underthrusting.* The depths of the deepest earthquakes, the presence of volcanism, and the occurrence of tsunamis (seismic sea waves) seem to be related closely to the present rates of underthrusting in island arcs. In the series of arcs that stretches from Tonga to the Macquarie ridge the depths of the deepest earthquakes generally decrease from about 690 km in the north to less than 100 km in the south [*Hamilton and Evison*, 1968]. The rates of underthrusting computed by Le Pichon also decrease from north to south. Volcanic activity, which is prominent north of the South Island of New Zealand, dies out when the deepest part of the seismic zone shoals to depths less than about 100 to 200 km. Similarly, the depth of deepest activity in the Aleutian arc and the number of volcanoes (Figure 2) appear to decrease from east to west as the rate of underthrusting decreases. In this arc the rate of underthrusting decreases because the slip vectors become more nearly parallel to the arc. Volcanism and the depth of seismic activity increase spectacularly as the slip vectors change from a predominance of strike-slip motion in the western Aleutians to largely dip-slip motion in Kamchatka, the Kurile Islands, and Japan. Most of the world's active volcanoes are located either along the world rift system or in regions that contain intermediate-depth earthquakes. Hence, the latter volcanoes are presumably located in the regions where the lithosphere has been underthrust to depths of at least 100 km.

*Tsunamis.* Although some prominent seismologists (e.g., *Gutenberg* [1939]) have argued that some of the largest tsunamis (seismic sea waves) are generated by submarine slides, many other geophysicists maintained that sudden dip-slip motion along faults during large earthquakes is the principal generating mechanism for most of the world's more widespread tsunamis. L. Bailey (personal communication), following a lecture by Sykes, suggested that tsunami generation might correlate with areas of large dip-slip motion. This suggestion may have considerable merit.

Figure 2 shows the epicenters of earthquakes for which tsunamis were detected at distances of 1000 km or greater [*Heck*, 1947; *Gutenberg and Richter*, 1954; *U. S. Coast and Geodetic Survey*, 1935–1965]. The distance criterion was used to eliminate waves of more local origin, some of which actually may be related to seiches or to submarine slides. Although this compilation undoubtedly is not complete even for the present century, the conclusions drawn here should not be seriously affected by the choice of data.

Since most of the earthquakes generating tsunamis are located in regions that are characterized by a high rate of dip-slip motion (Figure 2), the two phenomena appear to be causally related in many cases. Although most of the world's largest earthquakes occur in these areas and are characterized by a large component of thrust faulting, large earthquakes along major strike-slip faults near the coasts of southeast Alaska and British Columbia have not generated sea waves that were observable at distances greater than about 100 km. An earthquake located off the coast of California in 1927, however, generated a wave detected in Hawaii [*Gutenberg and Richter*, 1954]. Other generating mechanisms, such as volcanic eruptions and submarine slumping, cannot be excluded as the causative agents for at least some tsunamis.

*Gutenberg* [1939] argued that the epicenters of several earthquakes generating tsunamis were located on land. Although the epicenter, which represents the point of initial rupture, may be located inland, the actual zone of rupture in great earthquakes is now known to extend for several hundred kilometers. In many of the great earthquakes associated with island arcs and with active continental margins at least a portion of the zone of rupture is located in water-covered areas. Hence, the location of the epicenter itself is not an argument for the absence of significant vertical displacements in nearby submarine areas. *Utsu* [1967] has shown that, as a result of the anomalous zones in the mantle beneath island arcs, locations of shallow shocks based on teleseismic data are usually landward of the actual location. Both improved locations based on a better knowledge of seismic wave travel times in anomalous regions such as island arcs and rapid determinations of focal mechanisms may be of substantial value in tsunami warning systems.

*Length of seismic zones in island arcs.* The systematic changes in the seismic zones in the Aleutians and in the southwest Pacific suggest that the lengths of zones of deep earthquakes might be a measure of the amount of underthrusting during the last several million years. Using the maps of deep and intermediate-depth earthquakes prepared by *Gutenberg and Richter* [1954], *Oliver and Isacks* [1968] estimated the area of these zones and divided the total area by the length of the world rift system (about two great circles) and by 10 m.y., which is the duration of the latest cycle of spreading based on data from ocean-floor sediments and from magnetics [*Ewing and Ewing*, 1967; *Vine*, 1966]. They obtained an average rate of spreading for the entire rift system of 1.3 cm/yr for the half-velocity. This value is reasonable for the average velocity of spreading along the world rift system.

The hypothesis that the lengths of deep seismic zones are a measure of the amount of underthrusting during the past 10 m.y. is examined in greater detail in Figure 16 and in Table 1. Figure 16 illustrates the lengths of the seismic zones in various arcs and the corresponding rates of underthrusting as calculated by *Le Pichon* [1968] from observed velocities of sea-floor spreading and the orientation of fracture zones along the world rift system. In nearly all cases the regions with the deepest earthquakes (and hence the longest seismic zones as measured along the zones and perpendicular to the arcs) correspond to the areas with the greatest rates of underthrusting; regions with only shallow- and intermediate-depth events are typified by lower rates of underthrusting. Since the calculated slip rates and some of the measured lengths may be uncertain by 20% or more, the correlation between the two variables is, in fact, surprisingly good.

Although six points fall well above a line of unit slope, which represents an age of 10 m.y., all but one of the lengths are within a factor of 2 of the lengths predicted from the hypothesis that these zones represent materials underthrust during the last 10 m.y. Three of the more discrepant points, which are denoted by crosses on the figure, represent a small number of deep earthquakes that are located in

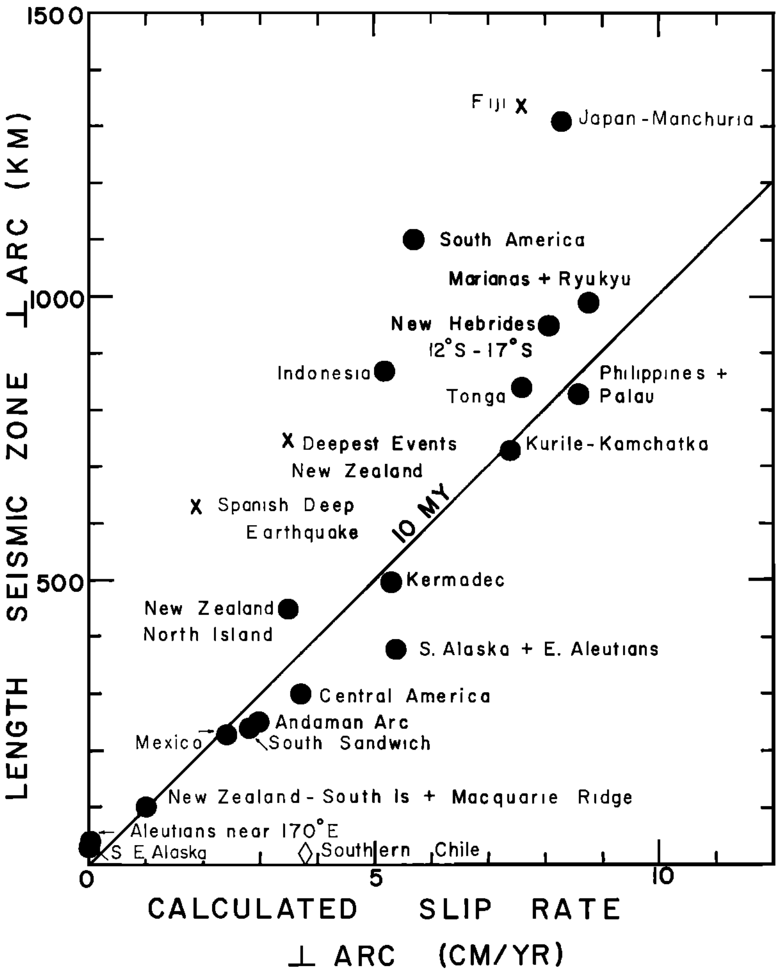



Fig. 16. Calculated rates of underthrusting [*Le Pichon*, 1968], and length of seismic zone for various island arcs and arc-like features (solid circles), for several unusual deep events (crosses), and for Southern Chile (diamond). The solid line indicates the theoretical locus of points for uniform spreading over a 10-m.y. interval.

TABLE 1. Comparison of Estimated Slip Rates for Three Island Arcs
Values are in centimeters per year.

| Island Arc | Slip Rate from Shallow-Focus Seismicity, after *Brune* [1968] | Calculated Slip Rate, Data from Ocean Ridges, after *Le Pichon* [1968] | Slip Rate* Assuming Length Seismic Zone Measures Amount Underthrust during Last 10 m.y. |
|---|---|---|---|
| Tonga | 5.2 | 7.6 | 8.4 |
| Japan | 15.7 | 8.8 | 16.3 |
| Aleutians | 3.8 | 6.1 | 4.0 |

* Corrected for azimuth of slip vector using data of *Le Pichon* [1968]. Rates given for the three methods are the magnitudes of the total slip vectors and not the magnitudes of the dip-slip components used in Figure 16.

unusual locations with respect to the more active, planar zones of deep earthquakes. They include the unusual deep Spanish earthquake of 1954, three deep earthquakes in New Zealand, and a few deep events under Fiji that appear to fall between the deep zones in the Tonga and New Hebrides arcs.

*Other estimates of slip rates in island arcs.* Slip rates for Tonga, Japan, and the Aleutians (Table 1) were calculated (1) from the dislocation theory using data on the past occurrence of earthquakes [*Brune*, 1968], (2) from the observed spreading velocities along ocean ridges assuming that all of the spreading is absorbed by underthrusting in island arcs [*Le Pichon*, 1968], and (3) from the lengths of the seismic zones assuming these lengths are a measure of the amount of underthrusting during the last 10 m.y. For each arc the three rates are within a factor of 2 of one another.

*The 10-m.y. isochron.* Two hypotheses may explain the correlation between the length of seismic zones and the computed rate of underthrusting (Figure 16). One theory, which was mentioned earlier, assumes that the present seismic zones in island arcs were created during a recent episode of spreading which began about 10 m.y. ago (Figure 14*a*). In the other hypothesis, 10 m.y. is regarded as the approximate time constant for assimilation of the lithosphere by the upper mantle (Figure 14*c*). Since the zone of anomalously high heat flow on ocean ridges appears to be confined to regions less than about 10 m.y. old [*McKenzie*, 1967; *Le Pichon and Langseth*, 1968], 10 m.y. is a reasonable time constant for the creation of the normal oceanic lithosphere. Hence, this value is not an unreasonable first approximation to the time constant for assimilation of the lithosphere in island arcs. It should be recognized, however, that the time constant for ocean ridges may be uncertain by more than a factor of 2 because of scatter in heat flow data. At present, it does not seem possible to ascertain which of the two alternative proposals (Figure 14*a* or 14*c*) governs the lengths of seismic zones in island arcs.

With the exception of the data for southern Chile (the diamond in Figure 16) there are no points lying significantly below the 10-m.y. isochron. A reduction in slope at the higher spreading rates might occur if the lithosphere were suddenly modified at a given depth through warming or a phase change that would prevent deeper earthquakes from occurring. These processes apparently have not led to significant decreases in the lengths of the seismic zones compared with those predicted by the 10-m.y. isochron in Figure 16.

*Southern Chile.* In southern Chile between 46° and 54°S, the absence of observable deep activity, the near-absence of shallow seismicity, and the presence of a sediment-filled trench [*Ewing*, 1963; *Hayes*, 1966] are in obvious conflict with the predicted length of the seismic zone. Le Pichon's omission of two very active features, the West Chile ridge and the Galapagos rift zone (Figure 15) in his analysis may, however, explain this discrepancy. *Wilson* [1965*a*] argued that since Antarctica is almost surrounded by spreading ridges, the coast of South America south of its juncture with the

West Chile ridge at 46°S should not be seismically active. An alternative explanation for the near-absence of shallow seismicity is that activity during the past 70 years of instrumental seismology is not representative of the long-term activity. This explanation is, however, difficult to apply to the hypothetical deep seismic zone that is predicted from Le Pichon's calculations. Hence, we feel that either Wilson's proposal or some other explanation is needed to account for the tectonics of southern Chile.

*Departures from the 10-m.y. isochron.* Several factors could explain the six points that fall well above the 10-m.y. isochron in Figure 16: (1) Some pieces of lithosphere became detached from the main dipping zones of deep activity by active processes, such as gravitational settling of slabs of lithosphere or convection currents in the asthenosphere (Figure 14*d*). (2) The initiation of underthrusting and spreading was not simultaneous in all regions. (3) Some or all anomalous deep events may be related to previous episodes of underthrusting. (4) The computed slip rates are not correct. (5) If the thermal time constant for assimilation of the lithosphere is generally about 10 m.y. (Figure 14*c*), the anomalous points may represent pieces of lithosphere with anomalously high time constants so that they are not completely assimilated.

Although some of the computed spreading rates may be in error (particularly the values for Indonesia and South America may be in error because the magnetic data in the Indian Ocean are poor and because the West Chile ridge and the Galapagos rift zone (Figure 14) were not included in Le Pichon's analysis), it is difficult to argue that these rates are greatly in error for each of the six anomalous points. The possible ramifications of the various alternative proposals should be exciting enough to encourage further study of these new approaches to the distribution of deep earthquakes.

*Interaction of continental blocks of lithosphere.* The Alpide belt, which comprises much of the Mediterranean region, the Middle East, and large parts of central and southern Asia, was not included in Figure 16 because it is very difficult to define the total amount of underthrusting. Seismic actvity in the Alpide zone, unlike that along either the ocean ridges or the typical island arcs, occupies a very broad region (Figure 15). Spreading in the Indian Ocean is apparently being absorbed in several subzones within the Alpide belt. This conclusion is supported by the widespread distribution of large shallow earthquakes and by the relatively small number of intermediate- and deep-focus earthquakes [*Gutenberg and Richter*, 1954].

Although, in principle, it seems reasonable to describe the tectonics of Eurasia by the interaction of blocks of lithosphere, it is not yet clear how successful this idea will be in practice because of the large number of blocks involved. The interaction of blocks of lithosphere appears to be much more complex when all the blocks are continents or pieces of continents than when at least one is an oceanic block. In addition to activity in the Alpide belt, earthquakes in East Africa, northern Siberia, and western North America (including Alaska) are more diffused in areal extent (Figure 15). In contrast, seismic zones associated with ocean ridges, island arcs, and many active continental margins appear to be extremely narrow and well defined. Several factors may explain these differences: (1) The lithosphere may be more heterogeneous in some or all continental areas and, hence, may break in a more complex fashion. (2) Old zones of weakness in continental areas may be reactivated. (3) Because of its relatively low density, it may not be possible to underthrust a block of *continental* lithosphere into the mantle to depths of several hundred kilometers. This third point is supported by the relatively large areas of older continental rocks.

As much of the sea floor appears to be relatively young, plates of oceanic lithosphere probably do not contain a large number of zones of weakness, whereas the continental plates, which are older, seem to contain many zones of weakness. Except for a few earthquakes along the extensions of fracture zones, the ocean basins are extremely quiet seismically. Continents, however, exhibit a low level of activity in many areas that do not appear to be undergoing strong deformation. This contrast in activity does not appear to be an artifact of the detection system but rather appears to be related to the different character of the oceanic and continental lithosphere.

One exception to this rule is the near-absence of observable activity in Antarctica. Unlike the other continents, Antarctica is almost surrounded by ocean ridges that are probably migrating outwardly [*Wilson,* 1965*a*]. Hence, the antarctic plate may not be subjected to stresses as large as the stresses occurring in other continents.

*Summary of evidence for global movements.* The concentration of seismic activity and the consistency of individual mechanism solutions for mid-ocean ridges, for island arcs, and for most of the world's active continental margins indicate that tectonic models involving a few plates are highly applicable for these areas. Since individual mechanism solutions in a given region are highly coherent, each solution may be regarded as an extremely pertinent datum. It is not necessary to resort to complex statistical methods for analyzing the relative motions of these large blocks. For these regions much of the scatter in many previous mechanism studies appears to be largely a result of poor seismic data and errors in analysis. Although the concept of interacting blocks of lithosphere may not be as easily applied to the complex interactions of continental blocks in such areas as the Alpide belt, a consistent (but complex) tectonic pattern may yet emerge when the pattern of seismicity is well defined and when a sufficiently large number of high-quality mechanism solutions is available. Thus, the new global tectonics among other things appears to explain most of the major seismic zones of the world, the distribution and configuration of the zones of intermediate and deep earthquakes, the focal mechanisms of earthquakes in many areas, and the distribution of a large number of the world's active volcanoes.

## Additional Evidence for Existence of Lithosphere, Asthenosphere, and Mesosphere

*Complex tectonic patterns near the earth's surface.* A number of objections have been raised to models of sea-floor spreading that involve simple symmetrical convection cells extending from great depths to the surface of the earth. They include such statements as: Since the Atlantic and Indian oceans are both spreading, the tectonics of Africa should be of a compressional nature rather than of an extensional nature, as reported for the East African rift valleys; if spreading from the eastern flank of the East Pacific rise near Mexico is absorbed only a few hundred kilometers from the rise in the Middle America trench, it is difficult to imagine how materials on the western flank of the rise travel more than 10,000 km before they are absorbed in the trenches of the western Pacific. Although some of the fracture zones on ocean ridges may be as long as 1000 km, some of these zones are less than 50 to 100 km apart. It is almost impossible to believe that these long narrow strips reflect the shape of independent convection cells. These and several similar dilemmas may be resolved if a layer of greater strength (the lithosphere) overlies a region of much lesser strength (the asthenosphere).

The configuration of the asthenosphere and of the various pieces of lithosphere may in some ways be analogous to blocks of ice floating on water. Although the surface pattern of the ice may be very complex, the pattern of convection in the water below or in the air above may be very simple, or it may be complex and of a completely different character than that of the motions of the ice. This analogy may be relevant to the more complex nonsymmetrical tectonic pattern exhibited by the earth's surface. A lithospheric model readily accounts for the asymmetrical structure of island arcs and for the symmetrical configuration of ocean ridges. It also explains the rather smooth variations in rates of spreading in a given ocean.

In this model the ridges and island arcs are dynamic features, and hence they appear to move with respect to one another. Thus, a region of extensional tectonism may be located between two spreading ridges. What is demanded in this model, however, is that surface area be conserved on a worldwide basis. To what extent the motions of large plates of lithosphere are coupled to motions in the asthenosphere remains an unsolved problem.

*Depths of earthquakes along the world rift system.* The existence of a layer of strength near the earth's surface is compatible with the observation that all earthquakes on the ocean ridges are apparently of shallow focus (i.e., less than a few tens of kilometers deep). Using a dislocation model, *Brune* [1968] estimated that the zone of earthquake generation for some oceanic fracture zones appears to be less than 10 km in vertical extent.

The San Andreas fault of California appears to be a major transform fault connecting growing ocean ridges off the west coast of Oregon and Washington with spreading ridges in the Gulf of California (Figure 3). Observed seismic activity along the San Andreas system is confined to the upper 20 km of the earth, and much of this activity is confined to the upper 5 or 10 km [*Press and Brace,* 1966]. Most estimates of the depths of faulting in the great San Francisco earthquake of 1906, the Imperial Valley earthquake of 1940, and the Parkfield earthquake of 1966 are within the upper 10 to 20 km of the earth [*Kasahara,* 1957; *Byerly and DeNoyer,* 1958; *Chinnery,* 1961; *McEvilly et al.,* 1967; *Eaton,* 1967]. Since displacements of at least 100 km (and probably 300 to 500 km) probably have occurred along the San Andreas fault [*Hamilton and Meyers,* 1966], it is almost certain that deformation by creep without observable earthquake activity must be occurring at depths greater than 20 km. Thus, an upper layer of strength in which earthquakes occur associated with a zone of low strength below seems to be demanded for California and for other parts of the world rift system.

*Variations in thickness of the lithosphere along the world rift system.* Although earthquakes on the mid-Atlantic, mid-Indian, and Arctic ridges occur along the ridge crests themselves as well as along fracture zones, observable seismic activity along much of the East Pacific rise is concentrated almost exclusively along fracture zones [*Menard,* 1966; *Tobin and Sykes,* 1968]. With the exception of the Gorda ridge off northern California, which appears to be spreading relatively slowly, earthquakes are only rarely recorded from the crest of most of the East Pacific rise. Since evidence from magnetic anomalies indicates a relatively fast rate of spreading (greater than 3 cm/yr for the past 1 m.y.) along much of the East Pacific rise [*Heirtzler et al.,* 1968] and since earthquakes are present on the bounding transform faults, much of the crest of this rise appears to be spreading by ductile flow with little or no observable seismic activity.

*Menard* [1967] and *van Andel and Bowin* [1968] observed that ridges with spreading rates higher than about 3 cm/yr are typified by fairly smooth relief, a thin crest, and the absence of a median rift valley. Ridges with lower spreading rates are, however, characterized by high relief, a thick crust, and a well-developed median valley. *van Andel and Bowin* [1968] suggest that materials undergoing brittle fracture may be thin at sites of faster spreading because higher temperatures might occur at shallower depths. The crest of the East Pacific rise is characterized by heat flow anomalies that are broader and apparently of greater amplitude than the anomalies associated with ridge crests in the Atlantic and Indian oceans [*Le Pichon and Langseth,* 1968]. Thus, higher temperatures beneath the East Pacific rise may suppress the buildup of stresses large enough to generate observable seismic activity.

If the occurrence of earthquakes and the presence of a median rift valley correlate with high strength and their absences (in spite of large deformations) correlate with low strength, the lithosphere may be very thin or almost nonexistent near the crest of the East Pacific rise. The lithosphere must be present, however, within a few tens of kilometers or less of the crest to account for the much higher seismic activity along fracture zones. It is possible that seismic activity along the crest of the East Pacific rise may occur mainly as small earthquakes that either are not detected or are rarely detected by the present network of seismograph stations. A microearthquake study using either hydrophones or ocean-bottom seismographs could furnish important information about the mode of deformation at the crest of these submarine ridges.

*High-frequency $S_n$ waves crossing ocean ridges. Molnar and Oliver* [1968] studied $S_n$ propagation in the upper mantle for about fifteen hundred paths; they did not observe any high-frequency $S_n$ waves for ocean paths that either originate at or cross an active ridge crest. Their observations also suggest that the uppermost mantle directly beneath ridge crests is not included in the lithosphere but that the uppermost mantle must be included in the lithosphere beyond about 200 km of the crest in order to explain the propagation of high-frequency $S_n$ from several events on some of the larger fracture zones. The distance for any given ridge may depend on the spreading rate, but the data were inadequate to confirm this assumption. The thinning or near-absence of lithosphere in a zone near the ridge crest would be compatible with the magmatic emplacement of the lithosphere near the crests of ocean ridges and with a gradual thickening of this layer as it cools and moves away from the crest. This thinning may also explain the maintenance of near-isostatic equilibrium over ocean ridges [*Talwani et al.*, 1965*a*].

*Thickness of the lithosphere from heat flow anomalies.* If the spreading rates inferred from magnetic anomalies are accepted, the calculated heat flow anomaly over ridges for a model of a simple mantle convection current that extends to the surface is not compatible with the observed heat flow anomaly [*Langseth et al.*, 1966; *Bott*, 1967; *McKenzie*, 1967]. These observations are, however, compatible with the computed heat flow for a simple model of cooling lithospheric plate approximately 50 km thick [*McKenzie*, 1967]. In this model the heat flow anomaly results from the cooling of the lithosphere after it is emplaced magmatically near the axis of the ridge. Because of the scatter in the heat flow data and because of the simplifying assumptions used to obtain the estimate of 50 km, the value for the thickness either may be uncertain or may vary by a factor of 2 or more. The occurrence of earthquakes as deep as 60 km beneath Hawaii [*Eaton*, 1962] may also be used as an estimate of the thickness of the lithosphere. *Orowan* [1966] tried to fit the observed heat flow pattern for ridges with models in which the crust is stretched on the ridge flanks and the rate of spreading is a function of distance from the ridge. His model does not appear to be compatible either with the symmetry of magnetic anomalies close to the ridge or with the narrow width of the seismic zones on most ocean ridges.

*Maximum sizes of earthquakes.* The sizes of the largest earthquakes along ocean ridges and along island arcs may be related to the thickness of the lithosphere in each of these tectonic provinces. The world rift system (including California, southeast Alaska, and east Africa) accounts for less than 9% of the world's earthquakes and for less than 6% of the seismic energy in earthquakes; island arcs and similar arcuate structures contribute more than 90% of the world's energy for shallow earthquakes and nearly all the energy for deep earthquakes [*Gutenberg and Richter*, 1954]. The relatively small amount of seismic activity on the ridge system and its largely submarine environment probably explain why the significance and the worldwide nature of this tectonic feature were not clearly recognized until about 12 years ago.

Although *Richter* [1958] lists more than 175 very large earthquakes (magnitude $M$ greater than or equal to 7.9) as originating in arcs and arc-like features, he reports only 5 events of this size for the world rift system. Whereas the largest event on the ridge system was of magnitude 8.4, the largest known earthquakes from island arcs were of magnitude 8.9. This difference in magnitude corresponds to about 8 times as much energy in the larger shocks. Most (and perhaps all) of the earthquakes on the ridge system with magnitudes greater than about 7 appear to have occurred along major transform faults.

Thus, the maximum magnitudes of earthquakes during the last 70 years for various tectonic features may be summarized as follows: island arcs, 8.9; major fracture zones, 8.4; ridge crests in the Atlantic, Indian, and Arctic oceans, about 7; most of the crest of the East Pacific rise (with the exception of the Gorda ridge), few (and possibly no) events larger than 5. The relative frequencies of very large earthquakes and possibly the upper limits to the sizes of earthquakes appear to be related to the area of contact between pieces of lithosphere that move with respect to one another. On the crest of the East Pacific rise the zone of contact between brittle materials is either absent or is confined to a thin surficial layer; at the crests of other ridges the lithosphere appears to be somewhat thicker. For fracture zones the thickness of the lithosphere may be as great as a few tens of kilometers; thus, the maximum magnitudes may be limited by the length of the fracture zone and by the thickness of the lithosphere. In island arcs the thickness of the lithosphere may be greater than that on the ridges because the temperatures beneath ridges are higher and perhaps because some material is added to the bottom of the lithosphere as it moves away from a ridge crest. Since the dip of seismic zones in island arcs usually is not vertical, the area of contact between plates of lithosphere may be increased by this factor alone. For example, the zone of slippage in the great Alaska earthquake of 1964 appears to dip northwesterly at a shallow angle (about 10°) and to extend for about 200 km perpendicular to the Aleutian island arc [*Plafker*, 1965; *Savage and Hastie*, 1966]. Since the dip is shallow, this zone does not extend more than about 40 km below the surface at its deepest point. Thus, it is not unreasonable that much greater amounts of elastic energy can be stored and released along island arcs than along the mid-ocean ridges.

Since single great earthquakes apparently have not involved a rupture that extended along the entire length of the larger island arcs [*Richter*, 1958], some other factor appears to limit the length of rupture and hence the maximum sizes of earthquakes. Tear faults (i.e., transform faults of the arc-arc type) within the upper thrust plate may divide island arcs into smaller subprovinces that are not completely coupled mechanically.

*Some properties of the lithosphere and asthenosphere.* Thus far we have defined the lithosphere as a layer of high strength and the asthenosphere as a layer of low strength. Since the rheological properties of the mantle are not at all well understood, we have purposely used the term strength in a general sense without being more specific about the actual mechanisms of deformation. Thus, it is not at all certain that various techniques for measuring the thickness and the presence of the lithosphere necessarily yield comparable values since these methods probably sample different physical parameters. It is encouraging, however, that estimates of the thickness of the lithosphere from analyses of heat flow anomalies, the absence of earthquakes (in spite of large deformation), the requirements of isostasy and the maintenance of mountains [*Daly*, 1940], the amplitudes and wavelengths of gravity anomalies [*McKenzie*, 1967], the propagation of high-frequency $S_n$ waves, and a transition in the types of earthquake mechanisms in island arcs are about 100 km or less. It is not clear, however, to what extent the variations in these estimates represent real differences in thickness or merely differences in the relations between thickness and the various physical parameters measured.

The asthenosphere in the three-layered model shown in Figure 1 also roughly coincides with the low-velocity zone for $S$ waves [*Gutenberg*, 1959; *Dorman et al.*, 1960; *Anderson*, 1966; *Ibrahim and Nuttli*, 1967], regions of either low velocity or nearly constant velocity for $P$ waves [*Lehmann*, 1964*a, b*] and of low density or nearly constant density [*Pekeris*, 1966], a region of high attenuation for seismic waves, particularly $S$ waves [*Anderson and Archambeau*, 1964; *Anderson*, 1967*b*; *Oliver and Isacks*, 1967], and a low-viscosity zone in the upper mantle [*McConnell*, 1965]. Although these observations yield very little information about the actual mechanisms of dissipation, they are consistent with the hypothesis that the asthenosphere is a region of low strength bounded below by the mesosphere, a region of greater strength. The simplest explanation for these phenomena is that the closest approach to melting (or partial melting) occurs in the asthenosphere. That relative displacements of the earth's surface may be modeled by a series of moving plates is a strong argument for a region of low strength (the asthenosphere) in the upper mantle. Nevertheless, the physical properties and configuration of the asthenosphere and the lithosphere may vary from place to place. In fact, variations of these types seem to be required to account for many of the complexities of the outer few hundred kilometers of the earth. The evidence for such lateral variations is now so strong as to demand reevaluation of studies of velocity and $Q$ structure based on models that consist only of concentric spherical shells.

## Conflicting Seismological Evidence and Some Problems

The new global tectonics, in one form or another, has been remarkably successful in explaining many gross features and observations of geology, but its development must be continued in an effort to establish a theory that is effective throughout the earth sciences at levels of increasingly greater detail. Many difficult problems remain. A quantitative understanding of the processes in the mantle that result in the observed surface features is urgently needed. The roles of the earth's initial heat, gravitational energy, radioactive heat, and phase changes must be understood. The mechanics of flow in the mantle is little known. The history of sea-floor spreading through geologic time and the relation between the vast quantities of geologic observations and the hypotheses must be worked out. A vital unanswered question is why island arcs and ocean ridges have their particular characteristic patterns. These grand questions are of concern to seismologists, not only because there is general interest in the hypotheses but also because the solutions may very well be dependent on evidence from seismology. In the absence of all but the most preliminary attempts to solve these problems, however, it is difficult to speculate on the direction and force of the evidence. At the present there appears to be no evidence from seismology that cannot eventually be reconciled with the new global tectonics in some form. Some traditional views that once would have appeared contradictory (such as, for example, the assignment of substantial rigidity to the entire mantle over a long time interval because of efficient propagation of shear waves with periods of about 10 sec) have long been discounted on the basis of information on glacial rebound, gravity, and, more recently, creep along long strike-slip faults, such as the San Andreas fault. That deep earthquakes generate shear waves and radiate waves in a pattern characteristic of a shear dislocation can hardly be taken as evidence for strength throughout the mantle in that depth range in light of a hypothesis that suggests that the mantle in the deep earthquake zones is much different from the mantle at comparable depths elsewhere.

The arc-like patterns of the active zone is but one of the problems of a subject that might be termed 'lithosphere mechanics.' Others are the shape of the deep zones, which sometimes appear to be near-planar after turning a rather sharp corner near the surface; the distribution of stress and strain in the lithosphere, not merely in active seismic areas but throughout the world; the interaction of lithosphere and asthenosphere; and flow in the asthenosphere.

Some specific evidence from seismology that does not readily fit into the new global tectonics at present does exist, however. For example, the locations of the Spanish deep earthquake and certain deep shocks in New Zealand and Fiji are not easily explained by current thinking, as has been pointed out above. The patterns of minor seismicity, including an occasional large earthquake in certain continental areas such as the St. Lawrence Valley and the Rocky Mountains and broad regional scattering of epicenters as in east Africa, are not simply explained as yet, nor is the almost complete lack of earthquakes in the oceanic lithosphere, which presumably can and does transmit stress over large distances. The occurrence of large active strike-slip faults that trend along the arc structure, such as the Alpine fault in New Zealand, the Philippine fault, the North Anatolian fault in Turkey, and the Atacama fault in Chile, ofters some diffculties. Tentative explanations have been proposed for the Alpine and Philippine faults; therefore, this matter may be resolved. Perhaps related to this problem is the occurrence in island arcs of occasional earthquakes with large strike-slip components along faults subnormal to the arc. The tectonics of the arc can hardly be as simple as that implied by Figure 1.

A general problem involving seismology concerns contrasts between continental and oceanic areas [*MacDonald*, 1964, 1966]. Some studies [e.g., *Brune and Dorman*, 1963; *Toksöz and Anderson*, 1966] show corresponding structural differences to depths of several hundred kilometers. Are such differences contrary to the new global tectonics? Might the observations be equally well satisfied by other models that are compatible with requirements of the new hypotheses? A serious difficulty may arise here if they cannot. Comparable and related problems arise in other disciplines. Observation suggests that heat flow per unit area is about the same under the oceans as under the continents. If it is assumed that the heat flux is largely due to radioactive decay and that radioactivity is heavily concentrated in certain continental rocks, lateral heterogeneity of the upper mantle is required and the mixing predicted by the new tectonics may be so great as to destroy such heterogeneity. Perhaps the amount of radioactivity in the earth has been highly overestimated, as has occasionally been suggested [*Verhoogen*, 1956], and much of the heat lost at the surface is transported from the deep interior by convection. More accurate determination of deep structure by seismological techniques is thus relevant to the problem of the amount of radioactivity in the earth and its distribution. Seismology is also vitally linked with heat flow in the island arcs, where low heat flow values appear to correlate with zones of descending lithosphere but anomalous high values appear over the deep seismic zones, and at the ocean ridges, where high heat flow may correspond with low strength and hence low seismic activity.

Other disciplines are also involved. The new structures based mainly on seismological information must be tested against gravity data. The record in the ocean sediments surely provides the most complete history of the ocean basins and hence must provide insight into seismological processes. Perhaps the crucial evidence on the validity of new global tectonics will come from cores of the entire sedimentary column of the ocean floor.

In petrology an interesting question concerns the origin of the belts of andesitic volcanoes. *Coats* [1962] proposed that ocean crust and sediments were thrust into the mantle under the Aleutian arc and subsequently erupted with mantle rock to account for the petrology of those islands. Can all the andesites of the active tectonic belts be explained in this manner? Are there any young (less than 10 m.y.) andesites of the same type that are *not* associated with active deep earthquake zones and arcs? Can this sort of information be used to identify ancient arcs?

The important problems arising from the new global tectonics are many; some are crucial. Evidence from seismology against the new global tectonics appears, however, to lack force.

## Effects of New Global Tectonics on Seismology

That seismology is providing abundant and important information for testing the new global tectonics is demonstrated in other sections of this paper and elsewhere. To date, most of the seismological work related to this topic has been so directed. The countering impact of the new global tectonics on seismology must also be carefully and thoroughly considered for indications of new directions for, and new attitudes toward, seismological research. This section is largely speculative and some of the points may seem farfetched. If, however, a basic understanding of global tectonics is imminent, even the most imaginative and wisest forecast of its effect on seismology is likely to be too conservative. Nor is seismology alone in this regard, for all branches of geology and geophysics related to the earth's interior will be comparably affected. The assumption that a major advance in our understanding of global tectonics has been achieved is tacit in the following.

Seismicity is an important branch of seismology and one that will be strongly affected by the impact of the new global tectonics. Such basic questions as why earthquakes occur largely in narrow belts separated by large stable blocks, why these belts are continuous on a worldwide scale, why they branch, why certain details of their configuration are as they are, why intermediate and deep earthquakes occur in some areas and not others are in the process of being answered today. There is every indication that the relation between seismic activity and geology will soon be understood to a much greater extent than contemplated heretofore. Improved accuracy in hypocenter location resulting from a better knowledge of velocity structure will facilitate this development. It will also assist in solving seismology's chief problem of a political nature, distinguishing between earthquakes and underground nuclear explosions. The self-consistent worldwide pattern of focal mechanisms will also be valuable here. Perhaps location of new seismograph stations in the proper relation to high-$Q$ zones within the earth will result in improved detection capability. Important questions still remain. For example, why have the earthquake belts and the associated tectonic belts assumed their present configuration? What can be learned about paleoseismicity and its relation to modern seismicity? How can the pattern of minor seismicity, including the occasional major earthquake outside the established seismic belts, be fit into the new global tectonics?

Closely related to the distribution of seismic events in time and space and to tectonics is the focal mechanism of the earthquake. Data of quality and quantity from modern observing stations can provide information for determination of focal mechanisms that severely test the new hypotheses and are crucial to their development. It appears that with only modest advances in technique properly documented earthquakes will provide reliable detailed information on tectonic activity. Focal mechanism, stress drop, slip, and orientation of principal stresses should be available from individual earthquakes, and singly or cumulatively these data will be integrated with the tectonic pattern.

Implicit in the new global tectonics is a new attitude toward mobility of the earth's strata. Measurements of fault creep and other forms of earth strain over recent short intervals of time are based on a variety of measuring techniques that include geodetic surveying, tide and strain gaging, and measurements of earthquake slip. Various methods of field geology give data extending over varying but greater intervals of time. When all these data are reduced to velocities that describe the motion of one point in the earth relative to another point located in an adjacent relatively underformed block, values are obtained that are in the same range as the velocity values associated with sea-floor spreading determined through analysis of geomagnetic data. This range is from about 1 to perhaps 10 cm/yr or more. These values are considerably higher than the values usually assumed in the past by most earth scientists considering deformation of this type; hence, new attitudes toward old problems must be anticipated. A prime example in seismology, cited above, is the association of the length along the dip of a deep seismic zone with the amount of relatively recent underthrusting in a region.

With the new global tectonics, interrelationships on a large, perhaps worldwide, scale can be predicted and perhaps observed. Thus, major seismic activity in one area could be related to that in an adjoining, or perhaps distant, area associated with the same lithospheric unit or units, for, although the propagation time for the effect may be long, stress may be transmitted over large distances through the lithosphere. Of special interest is the new insight into the subject of earthquake prediction, even prevention. Although an empirical method of prediction could by chance be found in the absence of an understanding of the process, an effective method is much more likely to be achieved if a basic understanding of the earthquake phenomenon is established. The new global tectonics offers great promise for such an achievement. It has already provided a theory that predicts over-all strain rates in tectonic areas throughout the world. It suggests a means for predicting the maximum size of an earthquake in a given region. It provides a framework in which to relate measurements of distortion, such as strains, tilts, and sea-level changes, with observations on the mechanism of the earthquake. It has established the continuity of active zones and has shown that apparently inactive segments of otherwise seismic belts must, indeed, be active, either by subsequent earthquakes or by creep. Refinements and further developments must be anticipated.

Seismology has long been the principal source of information on the structure of the earth's interior and is likely to continue in that role, with or without the new global tectonics. The new hypotheses will, however, certainly stimulate radically new approaches to the exploration of the earth's interior. A common and powerful technique of seismology involves the use of simplified earth models for prediction of certain observed effects. The new global tectonics calls for an entirely new kind of model. Layered models in which the shells are spherically symmetric are now outdated for many areas of the earth. Models based on the effect of spreading and growth of the lithosphere at the rifts and underthrusting at the island arcs must be tested against observation. The conventional division of the earth's surface into oceanic and continental areas, or oceanic, shield, and tectonic areas, requires a new look when the lithosphere, with its lateral variations, is involved. New models in which the age and the thickness of the lithosphere, as well as other properties, are taken into account are required.

In the new tectonics, information on properties and parameters such as attenuation, strength, creep, viscosity, and temperature is critically needed. Further efforts must be made to understand the relation between such properties and the seismic properties that are measured in a more straightforward manner. At the island arcs, where cold exotic materials are descending into the mantle, nature is performing the experiment of subjecting what are normally near-surface materials to the higher temperatures and pressures of the asthenosphere, an experiment in many respects much like the ones being performed in various laboratories. As our techniques for measuring the composition of the material and the dynamic and environmental parameters of this situation improve, this experiment should yield important information on many topics. Of great interest to seismologists is the long-standing problem of the mechanism of deep earthquakes. The radiation patterns of seismic waves from many events present a reasonably consistent pattern but one that cannot readily be explained in detail by existing hypotheses. The variation of seismic activity with depth is another source of information. Are the focal mechanisms of earthquakes at depth really as much like those in near-surface brittle materials as they seem? What is the role of water, of other interstitial fluid, of partial melting? Are phase changes in the exotic mantle materials important, perhaps not as sources of seismic waves but as concentrators of stress that leads ultimately to rupture? How are the seismic observations of focal mechanism, spatial and temporal distribution, energy, etc., related to the material of the mantle and what can we learn about that material? How are these data related to the general configuration of the seismic zone and of the geology of the island arc? These are some of the topics on which this experiment may provide information.

Surely, the most striking and perhaps the most significant effect of the new global tectonics on seismology will be an accentuated interplay between seismology and the many other disciplines of geology. The various disciplines which have tended to go their separate ways will find the attraction of the unifying concepts irresistible, and large numbers of refreshing and revealing interdisciplinary studies may be anticipated. For example, the geomorphology of an area of raised beaches takes on new light for those interested in paleoseismicity; the tectonic significance of a feature of the ocean floor is determined by its seismicity and by the mechanism of the earthquakes; the petrology of a volcano of an island arc is related in a meaningful way to the seismic activity below; the worldwide phenomena of seismology provide crucial evidence on the basic processes of the earth's interior that have shaped and are shaping the surficial features of interest to classical geology. Even if it is destined for discard at some time in the future, the new global tectonics is certain to have a healthy, stimulating, and unifying effect on all the earth sciences.

*Acknowledgments.* We thank Professor L. A. Alsop and Drs. Neil Opdyke and Walter Pitman for critically reading the manuscript. M. Barazangi, J. Dorman, W. Elsasser, R. Hamilton, X. Le Pichon, P. Molnar, W. J. Morgan, and W. Stauder, S. J., furnished preprints of their papers prior to publication. W. Ludwig of Lamont provided an original tracing of the seismic reflection profile of the Japan trench that was used in the paper. We appreciate and acknowledge discussions with many colleagues including J. Ewing, D. Griggs, D. McKenzie, and W. Pitman. Messrs. R. Laverty and J. Brock assisted in preparing the data for computation, and Mrs. Judith Healey assisted in editing and preparing the manuscript.

Computing facilities were made available by the NASA Goddard Space Flight Center, Institute for Space Studies, New York. This study was partially supported under Department of Commerce Grant E-22-100-68G from the Environmental Science Services Administration, through the National Science Foundation grant NSF GA-827, and through the Air Force Cambridge Research Laboratories, Office of Aerospace Research, under contract AF19(628)-4082 as part of the Advanced Research Projects Agency's Project Vela-uniform.

## References

Adams, R. D., Source characteristics of some deep New Zealand earthquakes, *New Zealand J. Geol. Geophys., 6,* 209, 1963.

Aki, K., Earthquake generating stress in Japan for the years 1961 to 1963 obtained by smoothing the first motion radiation patterns, *Bull. Earthquake Res. Inst. Tokyo Univ., 44,* 447, 1966.

Anderson, D. L., Recent evidence concerning the structure and composition of the earth's mantle, *Phys. Chem. Earth, 6,* 1, 1966.

Anderson, D. L., Phase changes in the upper mantle, *Science, 157,* 1165, 1967*a*.

Anderson, D. L., Latest information from seismic observations, in *The Earth's Mantle,* edited by T. F. Gaskell, p. 355, Academic Press, New York, 1967*b*.

Anderson, D. L., and C. B. Archambeau, The anelasticity of the earth, *J. Geophys. Res., 69,* 2071, 1964.

Badgley, P. C., *Structural and Tectonic Principles,* 521 pp., Harper and Row, New York, 1965.

Banghar, A., and L. R. Sykes, Focal mechanism of earthquakes in the Indian Ocean and adjacent areas, *J. Geophys. Res., 73,* in press, 1968.

Barazangi, M., and J. Dorman, World seismicity map of ESSA Coast and Geodetic Survey epicenter data for 1961–1967, *Bull. Seismol. Soc. Am., 58,* in press, 1968.

Benioff, H., Orogenesis and deep crustal structure: Additional evidence from seismology, *Bull. Geol. Soc. Am., 65,* 385, 1954.

Bodvarsson, G., and G. P. L. Walker, Crustal drift in Iceland, *Geophys. J., 8,* 285, 1964.

Bott, M. H. P., Terrestrial heat flow and the mantle convection hypothesis, *Geophys. J., 14,* 413, 1967.

Brune, J. N., Seismic moment, seismicity, and rate of slip along major fault zones, *J. Geophys. Res., 73,* 777, 1968.

Brune, J., and J. Dorman, Seismic waves and earth structure in the Canadian shield, *Bull. Seismol. Soc. Am., 53,* 167, 1963.

Bullard, E. C., Continental drift, *Quart. J. Geol. Soc. London, 120,* 1, 1964.

Bullard, E., J. E. Everett, and A. G. Smith, The fit of the continents around the Atlantic, *Phil. Trans. Roy. Soc. London, A, 258,* 41, 1965.

Burckle, L. H., J. Ewing, T. Saito, and R. Leyden, Tertiary sediment from the East Pacific rise, *Science, 157,* 537, 1967.

Byerly, P., and J. DeNoyer, Energy in earthquakes as computed from geodetic observations, in *Contributions in Geophysics in Honor of Beno Gutenberg,* edited by H. Benioff et al., p. 17, Pergamon Press, New York, 1958.

Carder, D. S., D. Tocher, C. Bufe, S. W. Stewart, J. Eisler, and E. Berg, Seismic wave arrivals from Longshot, 0° to 27°, *Bull. Seismol. Soc. Am., 57,* 573, 1967.

Chinnery, M. A., The deformation of the ground around surface faults, *Bull. Seismol. Soc. Am., 51,* 355, 1961.

Cleary, J., Azimuthal variation of the Longshot source term, *Earth Planetary Sci. Letters, 3,* 27, 1967.

Cleary, J., and A. L. Hales, An analysis of the travel times of *P* waves to North American stations, in the distance range 32°–100°, *Bull. Seismol. Soc. Am., 56,* 467, 1966.

Coats, R. R., Magma type and crustal structure in the Aleutian arc, in *The Crust of the Pacific Basin, Geophys. Monograph 6,* edited by G. A. Macdonald and H. Kuno, p. 92, American Geophysical Union, Washington, D. C., 1962.

Daly, R. A., *Strength and Structure of the Earth,* 434 pp., Prentice-Hall, Englewood Cliffs, N. J., 1940.

Dietz, R. S., Continent and ocean basin evolution by spreading of the sea floor, *Nature, 190,* 854, 1961.

Dorman, J., M. Ewing, and J. Oliver, Study of shear velocity distribution by mantle Rayleigh waves, *Bull. Seismol. Soc. Am., 50, 87,* 1960.

Dymond, J., and K. Deffeyes, K-Ar ages of deep-sea rocks and their relation to sea floor spreading (abstract), *Trans. Am. Geophys. Union, 49,* 364, 1968.

Eaton, J. P., Crustal structure and volcanism in Hawaii, in *The Crust of the Pacific Basin, Geophys. Monograph 6,* edited by G. A. Macdonald and H. Kuno, p. 13, American Geophysical Union, Washington, D. C., 1962.

Eaton, J. P., Instrumental seismic studies, in the Parkfield-Cholame, California, earthquakes of June–August 1966—surface geologic effects, water-resources aspects, and preliminary seismic data, *U. S. Geol. Surv. Prof. Paper 579,* p. 57, 1967.

Elsasser, W. M., Convection and stress propagation in the upper mantle, *Princeton Univ. Tech. Rept. 5,* June 15, 1967.

Ewing, J., and M. Ewing, Sediment distribution on the mid-ocean ridges with respect to spreading of the sea floor, *Science, 156,* 1590, 1967.

Ewing, M., Sediments of ocean basins, in *Man, Science, Learning, and Education,* p. 41, Rice University, Houston, Texas, 1963.

Ewing, M., J. Ewing, and M. Talwani, Sediment distribution in the oceans: The mid-Atlantic ridge, *Bull. Geol. Soc. Am., 75,* 17, 1964.

Ewing, M., and B. Heezen, Some problems of antarctic submarine geology, in *Antarctica in the International Geophysical Year, Geophys. Monograph 1,* edited by A. Crary et al., p. 75, American Geophysical Union, Washington, D. C., 1956.

Fedotov, S. A., A. M. Bagdasarova, I. P. Kuzin, R. Z. Tarakanov, and D. Yu. Shmidt., Seismicity and deep structure of the southern part of the Kurile Island arc, *Dokl. Akad. Nauk SSR, 153*(3), 668, 1963 (English translation, p. 71).

Fedotov, S. A., I. I. Kuzin, and M. F. Bobkob, Detailed seismological investigation of Kamchatka in 1961–1962, *Izv. Akad. Nauk SSSR, Ser. Geofiz., 9,* 1360, 1964.

Griggs, D. T., Reflections on the earthquake mechanism, in *Proceedings of the Second United States-Japan Conference on Research Related to Earthquake Prediction Problems,* edited by R. Page, p. 63, National Science Foundation, Washington, D. C. (also Japan Society for Promotion of Science, Tokyo), 1966.

Griggs, D. T., and D. W. Baker, The origin of deep-focus earthquakes, in *Properties of Matter,* p. 11, John Wiley, New York, in press, 1968.

Gunn, R., A quantitative study of mountain building on an unsymmetrical earth, *J. Franklin Inst., 224,* 19, 1937.

Gunn, R., Quantitative aspects of juxtaposed ocean deeps, mountain chains, and volcanic ranges, *Geophysics, 12,* 238, 1947.

Gutenberg, B., Tsunamis and earthquakes, *Bull. Seismol. Soc. Ann., 29,* 517, 1939.

Gutenberg, B., *Physics of the Earth's Interior,* 240 pp., Academic Press, New York, 1959.

Gutenberg, B., and C. F. Richter, *Seismicity of the Earth,* 2nd ed., Princeton University Press, Princeton, N. J., 1954.

Hamilton, R. M., and A. W. Gale, Seismicity and structure of the North Island, New Zealand, paper presented at 64th Annual Meeting of

Seismological Society of America, Tucson, Arizona, April 1968.

Hamilton, R. M., and F. F. Evison, Earthquakes at intermediate depths in southwest New Zealand, *New Zealand J. Geol. Geophys., 10,* 1319, 1968.

Hamilton, W., Origin of the Gulf of California, *Bull. Geol. Soc. Am., 72,* 1307, 1961.

Hamilton, W., and W. B. Meyers, Cenozoic tectonics of the western United States, *Rev. Geophys., 4,* 509, 1966.

Harding, S. T., and W. Rinehart, Preliminary seismological report, in *The Parkfield, California Earthquake of June 27, 1966,* p. 1, U.S. Government Printing Office, Washington, D. C., 1966.

Hayes, D. E., A geophysical investigation of the Peru-Chile trench, *Marine Geol., 4,* 309, 1966.

Heck, N. H., List of seismic sea waves, *Bull. Seismol. Soc. Am., 37,* 269, 1947.

Heirtzler, J. R., G. O. Dickson, E. M. Herron, W. C. Pitman, III, and X. Le Pichon, Marine magnetic anomalies, geomagnetic field reversals, and motions of the ocean floor and continents, *J. Geophys. Res., 73,* 2119, 1968.

Herrin, E., Travel-time anomalies and structure of the upper mantle (abstract), *Trans. Am. Geophys. Union, 47,* 44, 1966.

Herrin, E., and J. Taggart, Epicenter determinations for Longshot (abstract), *Trans. Am. Geophys. Union, 47,* 164, 1966.

Hess, H. H., Gravity anomalies and island arc structure with particular reference to the West Indies, *Proc. Am. Phil. Soc., 79,* 71, 1938.

Hess, H. H., History of the ocean basins, in *Petrological Studies: A Volume in Honor of A. F. Buddington,* edited by A. E. J. Engel et al., p. 599, Geological Society of America, New York, 1962.

Hirasawa, T., Source mechanism of the Niigata earthquake of June 16, 1964, as derived from body waves, *J. Phys. Earth, 13,* 35, 1965.

Hirasawa, T., A least-square method for the focal mechanism determinations from *S* wave data, 2, *Bull. Earthquake Res. Inst. Tokyo Univ., 44,* 919, 1966.

Hodgson, J. H., Nature of faulting in large earthquakes, *Bull. Geol. Soc. Am., 68,* 611, 1957.

Hodgson, J. H., and J. D. Cock, Direction of faulting in the deep focus Spanish earthquake of March 29, 1954, *Tellus, 8,* 321, 1956.

Hodgson, J. H., and A. E. Stevens, Seismicity and earthquake mechanism, *Res. Geophys., 2,* 27, 1964.

Holmes, A., *Principles of Physical Geology,* Ronald Press, New York, 1965.

Honda, H., A. Masatsuka, and K. Emura, On the mechanisms of the earthquakes and the stresses producing them in Japan and its vicinity, 2, *Sci. Rept. Tohoku Univ., Ser. 5, Geophys., 8,* 186, 1956.

Ibrahim, A., and O. W. Nuttli, Travel-time curves and upper-mantle structure from long period *S* waves, *Bull. Seismol. Soc. Am., 57,* 1063, 1967.

Ichikawa, M., Mechanism of earthquakes in and near Japan, 1950–1962, *Papers Meteorol. Geophys. Tokyo, 16,* 201, 1966.

Isacks, B. L., and L. R. Sykes, Focal mechanisms of deep and shallow earthquakes in the Tonga and Kermadec island arcs, in preparation, 1968.

Johnson, L. R., Array measurements of *P* velocities in the upper mantle, *J. Geophys. Res., 72,* 6309, 1967.

Kasahara, K., The nature of seismic origins as inferred from seismological and geodetic observations, 1, *Bull. Earthquake Res. Inst. Tokyo Univ., 35,* 473, 1957.

Katsumata, M., Seismic activities in and near Japan, 3: Seismic activities versus depth (in Japanese), *J. Seismol. Soc. Japan, 20,* 75, 1967.

Langseth, M. G., X. Le Pichon, and M. Ewing, Crustal structure of the mid-oceanic ridges, 5, Heat flow through the Atlantic Ocean floor and convection currents, *J. Geophys. Res., 71,* 5321, 1966.

Laughton, A. S., The Gulf of Aden, *Phil. Trans. Roy. Soc. London, A, 259,* 150, 1966.

Lehmann, I., On the travel times of *P* as determined from nuclear explosions, *Bull. Seismol. Soc. Am., 54,* 123, 1964*a*.

Lehmann, I., On the velocity of *P* in the upper mantle, *Bull. Seismol. Soc. Am., 54,* 1097, 1964*b*.

Le Pichon, X., Sea-floor spreading and continental drift, *J. Geophys. Res., 73,* 3661, 1968.

Le Pichon, X., and M. G. Langseth, Heat flow from the mid-oceanic ridges and sea-floor spreading, *J. Geophys. Res., 73,* in press, 1968.

Ludwig, W. J., J. I. Ewing, M. Ewing, S. Murauchi, N. Den, S. Asano, H. Hotta, M. Hayakawa, T. Asanuma, K. Ichikawa, and I. Noguchi, Sediments and structure of the Japan trench, *J. Geophys. Res., 71,* 2121, 1966.

MacDonald, G. J. F., The deep structure of continents, *Science, 143,* 921, 1964.

MacDonald, G. J. F., Mantle properties and continental drift, in *Continental Drift, Spec. Publ. 9,* edited by G. D. Garland, p. 18, Royal Society of Canada, Ottawa, 1966.

Matsuda, T., K. Nakamura, and A. Sugimura, Late Cenozoic orogeny in Japan, *Tectonophysics, 4,* 349, 1967.

Matthews, D. M., and J. Bath, Formation of magnetic anomaly pattern of mid-oceanic ridge, *Geophys. J., 13,* 349, 1967.

McConnell, R. K., Isostatic adjustment in a layered earth, *J. Geophys. Res., 70,* 5171, 1965.

McEvilly, T. V., W. H. Bakun, and K. B. Casaday, The Parkfield, California, earthquakes of 1966, *Bull. Seismol. Soc. Am., 57,* 1221, 1967.

McKenzie, D. P., Some remarks on heat flow and gravity anomalies, *J. Geophys. Res., 72,* 6261, 1967.

McKenzie, D., and R. L. Parker, The North Pacific: An example of tectonics on a sphere, *Nature, 216,* 1276, 1967.

Menard, H. W., Sea floor relief and mantle convection, *Phys. Chem. Earth, 6,* 315, 1965.

Menard, H. W., Fracture zones and offsets of the East Pacific rise, *J. Geophys. Res., 71,* 682, 1966.

Menard, H. W., Sea-floor spreading, topography, and the second layer, *Science, 157,* 923, 1967.

Minikami, T., Fundamental research for predicting volcanic eruptions, 1, Earthquakes and crustal deformations originating from volcanic activities, *Bull. Earthquake Res. Inst. Tokyo Univ., 38,* 497, 1960.

Mitronovas, W., L. Seeber, and B. Isacks, Earthquake distribution and seismic wave propagation in the upper 200 km of the Tonga island arc (abstract), *Trans. Am. Geophys. Union, 49,* 293, 1968.

Molnar, P., and J. Oliver, Lateral variation of attenuation in the upper mantle and discontinuities in the lithosphere, in preparation, 1968.

Morgan, W. J., Rises, trenches, great faults, and crustal blocks, *J. Geophys. Res., 73,* 1959, 1968.

Murphy, L. M., Worldwide seismic network, in *ESSA Symposium on Earthquake Prediction, February 1966,* p. 53, U.S. Government Printing Office, Washington, D. C., 1966.

Neumann, F., Crustal structure in the Puget Sound area, *IUGG Assoc. Seismol. Ser. A., Trav. Sci., 20,* 153, 1959.

Officer, C. B., J. Ewing, J. Hennion, D. Harkrider, and D. Miller, Geophysical investigations in the eastern Caribbean: Summary of 1955 and 1956 cruises, *Phys. Chem. Earth, 3,* 17, 1959.

Oliver, J., and B. Isacks, Deep earthquake zones, anomalous structures in the upper mantle, and the lithosphere, *J. Geophys. Res., 72,* 4259, 1967.

Oliver, J., and B. Isacks, Structure and mobility of the crust and mantle in the vicinity of island arcs, *Can. J. Earth Sci., 5,* in press, 1968.

Orowan, E., Age of the ocean floor, *Science, 154,* 413, 1966.

Parkin, E. J., *Alaskan Surveys to Determine Crustal Movement,* Part 2, *Horizontal Displacement, 15* pp., U. S. Department of Commerce, Washington, D. C., 1966.

Pekeris, C. L., The internal constitution of the earth, *Geophys. J., 11,* 85, 1966.

Pitman, W., and J. Heirtzler, Magnetic anomalies over the Pacific-Antarctic ridge, *Science, 154,* 1164, 1966.

Plafker, G. P., Tectonic deformation associated with the 1964 Alaska earthquake, *Science, 148,* 1675, 1965.

Plafker, G. P., and M. Rubin, Vertical tectonic displacements in south central Alaska during and prior to the great 1964 earthquake, *J. Geosci., Osaka Univ., 10,* 53, 1967.

Press, F., and W. F. Brace, Earthquake prediction, *Science, 152,* 1575, 1966.

Raitt, R. W., R. L. Fisher, and R. G. Mason, Tonga trench, *Geol. Soc. Am. Spec. Paper, 62,* 237, 1955.

Raleigh, C. B., Plastic deformation of upper mantle silicate minerals, *Geophys. J., 14,* 45, 1967.

Raleigh, C. B., and M. S. Paterson, Experimental deformation of serpentinite and its tectonic implications, *J. Geophys. Res., 70,* 3965, 1965.

Richter, C. F., *Elementary Seismology,* 768 pp., W. H. Freeman and Co., San Francisco, 1958.

Ritsema, A. R., Some reliable fault plane solutions, *Pure Appl. Geophys. 59,* 58, 1964.

Ritsema, A. R., The mechanism of some deep and intermediate earthquakes in the region of Japan, *Bull. Earthquake Res. Inst. Tokyo Univ., 43,* 39, 1965.

Savage, J. C., and L. M. Hastie, Surface deformation associated with dip-slip faulting, *J. Geophys. Res., 71,* 4897, 1966.

Scholl, E. W., R. Von Huene, and J. B. Ridlon, Spreading of the ocean floor: Undeformed sediments in the Peru-Chile trench, *Science, 159,* 869, 1968.

Sclater, J. G., V. Vacquier, J. P. Greenhouse, and F. S. Dixon, Melanesian subcontinent presentation and discussion of recent heat flow measurements (abstract), *Trans. Am. Geophys. Union, 49,* 217, 1968.

Stauder, W., *S* wave studies of earthquakes of the North Pacific, 1, Kamchatka, *Bull. Seismol. Soc. Am., 52,* 527, 1962.

Stauder, W., A comparison of multiple solutions of focal mechanisms, *Bull. Seismol. Soc. Am., 54,* 927, 1964.

Stauder, W., Earthquake mechanisms, *Trans. Am. Geophys. Union, 48,* 395, 1967.

Stauder, W., Mechanism of the Rat Island earthquake sequence of February 4, 1965, with relation to island arcs and sea-floor spreading, *J. Geophys. Res., 73,* 3847, 1968.

Stauder, W., S. J., and G. A. Bollinger, The *S*-wave project for focal mechanism studies, earthquakes of 1962, *Bull. Seismol. Soc. Am., 54,* 2198, 1964.

Stauder, W., S. J., and G. A. Bollinger, The *S*-wave project for focal mechanism studies, earthquakes of 1963, *Bull. Seismol. Soc. Am., 56,* 1363, 1966*a*.

Stauder, W., S. J., and G. A. Bollinger, The focal mechanism of the Alaska earthquake of March 28, 1964, and of its aftershock sequence, *J. Geophys. Res., 71,* 5283, 1966*b*.

Stauder, W., and A. Udias, *S*-wave studies of earthquakes of the North Pacific, 2, Aleutian Islands, *Bull. Seismol. Soc. Am., 53,* 59, 1963.

Sugimura, A., and S. Uyeda, A possible anisotropy in the upper mantle accounting for deep earthquake faulting, *Tectonophysics, 5,* 25, 1967.

Summerhayes, C. P., New Zealand region volcanism and structure, *Nature, 215,* 610, 1967.

Sykes, L. R., The seismicity and deep structure of island arcs, *J. Geophys. Res., 71,* 2981, 1966.

Sykes, L. R., Mechanism of earthquakes and nature of faulting on the mid-oceanic ridges, *J. Geophys. Res., 72,* 2131, 1967.

Sykes, L. R., Seismological evidence for transform faults, sea-floor spreading, and continental drift, in *Proceedings of NASA Symposium, History of the Earth's Crust,* edited by R. A. Phinney, Princeton University Press, Princeton, in press, 1968.

Sykes, L. R., B. Isacks, and J. Oliver, Earthquake swarms, volcanism, and sea-floor spreading, in preparation, 1968.

Talwani, M., and D. E. Hayes, Continuous gravity profiles over island arcs and deep sea trenches (abstract), *Trans. Am. Geophys. Union, 48,* 217, 1967.

Talwani, M., X. Le Pichon, and M. Ewing, Crustal structure of the mid-oceanic ridges, 2, Computed model from gravity and seismic refraction data, *J. Geophys. Res., 70,* 341, 1965*a*.

Talwani, M., X. Le Pichon, and J. R. Heirtzler, East Pacific rise: The magnetic pattern and the fracture zones, *Science, 150,* 1109, 1965*b*.

Talwani, M., G. H. Sutton, and J. L. Worzel, Crustal section across the Puerto Rico trench, *J. Geophys. Res., 64,* 1545, 1959.

Teng, T., Attenuation of body waves and the *Q* structure of the mantle, *J. Geophys. Res., 73,* 2195, 1968.

Tobin, D., and L. R. Sykes, Seismicity and tectonics of the northeast Pacific Ocean, *J. Geophys. Res., 73,* 3821, 1968.

Toksöz, M. N., and D. L. Anderson, Phase velocities of long-period surface waves and structure of the upper mantle, 1, Great-circle Love and Rayleigh wave data, *J. Geophys. Res., 71,* 1649, 1966.

Udias, A., and W. Stauder, Application of numerical methods for *S*-wave focal mechanism determination to earthquakes of Kamchatka-Kurile region, *Bull. Seismol. Soc. Am., 54,* 2049, 1964.

U. S. Coast and Geodetic Survey, *United States Earthquakes* (annual publications) ESSA, Rockville, Maryland, 1935–1965.

Utsu, T., Anomalies in seismic wave velocity and attenuation associated with a deep earthquake zone 1, *J. Fac. Sci. Hokkaido Univ. Japan, Ser. 7, Geophys., 3,* 1, 1967.

Uyeda, S., and K. Horai, Terrestrial heat flow in Japan, *J. Geophys. Res., 69,* 2121, 1964.

Vacquier, V., Magnetic evidence for horizontal displacements in the floor of the Pacific Ocean, in *Continental Drift,* edited by S. K. Runcorn, p. 135, Academic Press, New York, 1962.

van Andel, T. H., and C. O. Bowin, Mid-Atlantic ridge between 22° and 23° north latitude and the tectonics of mid-ocean rises, *J. Geophys. Res., 73,* 1279, 1968.

Vening Meinesz, F. A., Maritime gravity surveys in the Netherland East Indies, tentative interpretation of the results, *Koninkl. Ned. Akad. Wetenschap. Proc., B, 33,* 566, 1930.

Vening Meinesz, F. A., Indonesian Archipelago: A geophysical study, *Bull. Geol. Soc. Am., 65,* 143, 1954.

Verhoogen, J., Temperatures within the earth, *Phys. Chem. Earth, 1,* 17, 1956.

Vine, F. J., Spreading of the ocean floor: New evidence, *Science, 154,* 1405, 1966.

Vine, F. J., and P. M. Matthews, Magnetic anomalies over ocean ridges, *Nature, 199,* 947, 1963.

Vine, F. J., and W. J. Morgan, Simulation of mid-ocean ridge magnetic anomalies using a random injection model (abstract), *Program 1967 Ann. Meeting, Geol. Soc. Am.,* November 1967.

Vine, F. J., and J. T. Wilson, Magnetic anomalies over a young oceanic ridge off Vancouver Island, *Science, 150,* 485, 1965.

Wadati, K., T. Hirono, and T. Yumura, The absorption of transverse waves in the upper mantle under Japan (abstract), *Gen. Assembly IUGG Abstr. Papers, 2,* IASPEI-154, 1967.

Wegener, A., *The Origin of Continents and Oceans,* 4th ed., 246 pp., Dover, New York, 1966.

Wellman, H. W., New Zealand Quaternary tectonics, *Geol. Rundschau, 43,* 257, 1955.

Whitten, C. A., Measurements of earth movements in California, *Calif. Div. Mines Bull.,* 171, 75, 1955.

Whitten, C. A., Crustal movement in California and Nevada, *Trans. Am. Geophys. Union, 37,* 393, 1956.

Wilson, J. T., Evidence from islands on the spreading of ocean floors, *Nature, 197,* 536, 1963.

Wilson, J. T., A new class of faults and their bearing on continental drift, *Nature, 207,* 343, 1965*a*.

Wilson, J. T., Transform faults, oceanic ridges, and magnetic anomalies southwest of Vancouver Island, *Science, 150,* 482, 1965*b*.

Worzel, J. L., Deep structure of coastal margins and mid-oceanic ridges, *Colston Papers, 17,* 1965.

(Received May 21, 1968.)