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Mechanism of Earthquakes and Nature of Faulting on the Mid-Oceanic Ridges[1]

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The mechanisms of 17 earthquakes on the mid-oceanic ridges and their continental extensions were investigated using data from the World-Wide Standardized Seismograph Network of the U. S. Coast and Geodetic Survey and from other long-period seismograph instruments. Mechanism solutions of high precision can now be obtained for a large number of earthquakes with magnitudes as small as 6 in many areas of the world. Less than 1% of the data used in this study are inconsistent with a quadrant distribution of first motions of the phases *P* and *PKP*; in many previous investigations 15 to 20% of the data were often inconsistent with the published solutions. Ten of the earthquakes that were studied occurred on fracture zones that intersect the crest of the mid-oceanic ridge. The mechanism of each of the shocks that is located on a fracture zone is characterized by a predominance of strike-slip motion on a steeply dipping plane; the strike of one of the nodal planes for *P* waves is nearly coincident with the strike of the fracture zone. The sense of strike-slip motion in each of the ten solutions is in agreement with that predicted for transform faults; it is opposite to that expected for a simple offset of the ridge crest along the various fracture zones. The spatial distribution of earthquakes along fracture zones also seems to rule out the hypothesis of simple offset. Two well documented solutions for earthquakes that are located on the mid-Atlantic ridge but that do not appear to be located on fracture zones are characterized by a predominance of normal faulting. The mechanisms of four earthquakes on extensions of the mid-oceanic ridge system—one near northern Siberia and three in East Africa—are also characterized by a predominance of normal faulting. The inferred axes of maximum tension for these six events are approximately perpendicular to the strike of the mid-oceanic ridge system. The results are in agreement with hypotheses of sea-floor growth at the crest of the mid-oceanic ridge system.

INTRODUCTION

The discovery of a large number of fracture zones on the mid-oceanic ridges [*Menard,* 1955, 1965, 1966; *Heezen and Tharp,* 1961, 1965*a*] has led to a renewed interest in the existence of large horizontal displacements on the ocean floor and to reconsiderations of various hypotheses of sea-floor growth, continental drift, and convection currents. Evidence that magnetic anomalies on the ocean floor can be identified with past reversals in the earth's magnetic field [*Vine and Mathews,* 1963; *Vine and Wilson,* 1965; *Cann and Vine,* 1966; *Pitman and Heirtzler,* 1966; *Vine,* 1966] has added strong support to the hypothesis of ocean-floor spreading as postulated by *Hess* [1962] and *Dietz* [1961].

The offsets of magnetic anomalies and bathymetric contours at prominent fracture zones have been used as arguments for transcurrent fault displacements as great as 1000 km [*Vacquier,* 1962; *Menard,* 1965]. Nevertheless, several problems are raised about interpretations of this type. The inferred magnitude and sense of displacement are not always constant along a given fracture zone [*Menard,* 1965; *Talwani et al.,* 1965], and some fault zones appear to end quite abruptly [*Wilson,* 1965*a*]. In addition, seismic activity along fracture zones is concentrated almost exclusively between the two crests of the mid-oceanic ridge [*Sykes,* 1963, 1965]; very few earthquakes are found on the other portions of fracture zones.

Wilson [1965*a, b*] has presented arguments for a new class of faults—the transform fault. As an alternative proposal to transcurrent faulting, *Talwani et al.* [1965] have assumed that major faulting on fracture zones is normal faulting. Wilson and Talwani et al. assume that the various segments of the mid-oceanic ridge were never displaced at all but developed at their present locations. Hence, these theories and the

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transcurrent fault hypothesis predict different types of relative motion on the seismically active portions of fracture zones.

Since considerable interest now centers on the problem of large-scale deformation of the sea floor, it seemed imperative to inquire if the nature of relative displacements could be ascertained from an analysis of first motions of earthquakes that occur on the mid-oceanic ridges. Fortunately this interest in large horizontal displacements coincided with the advent of a significantly new source of seismological data. Long-period seismograph records from more than 125 stations of the World-Wide Standardized Seismograph Network (WWSSN) of the U. S. Coast and Geodetic Survey, from about 25 stations of the Canadian network, and from about 20 stations that cooperate with the Lamont Geological Observatory now furnish data of greater sensitivity, greater reliability, and broader geographical coverage than were available in most previous investigations of the mechanisms of earthquakes.

This paper presents data from 17 earthquakes on the mid-oceanic ridges and their extensions into East Africa and the Arctic. Nine of these events were located on the mid-Atlantic ridge, and three were situated on the east Pacific rise. This study of the mechanisms of earthquakes is in agreement in every case with the sense of motion predicted by *Wilson* [1965*a*, *b*] for transform faults. The results support the hypothesis of ocean-floor growth at the crest of the mid-oceanic ridge. The sense of displacement indicated from these studies of earthquakes is opposite to that expected for a simple offset of the ridge crest.

These investigations revealed two principal types of mechanisms for earthquakes on the mid-oceanic ridges. Earthquakes on fracture zones are characterized by a predominance of strike-slip motion; earthquakes located on the crest of the ridge but apparently not situated on fracture zones are characterized by a predominance of normal faulting. The inferred axes of maximum tension for these latter events are approximately perpendicular to the local strike of the ridge.

Previous Mechanism Solutions for Earthquakes on the Mid-Oceanic Ridges

Although more than a thousand mechanism solutions have been presented in the seismological literature, only about thirty are for earthquakes that occurred on the mid-oceanic ridges or on the extensions of this system into East Africa and the Arctic. Many of these solutions were based on a poor distribution of recording stations; many of the events were poorly recorded by the less sensitive network of instruments that existed before the advent of the WWSSN. *Hodgson and Stevens* [1964] concluded that almost none of these earthquakes on the ridge have yielded an unambiguous solution.

From an analysis of data from 13 shocks on the mid-Atlantic ridge *Misharina* [1964] concluded that the mechanisms were characterized by a predominance of strike-slip faulting. Unlike the results presented in this paper, however, the strikes of many of the nodal planes for *P* waves do not agree very closely with the strikes of the various fracture zones. Most of the data were obtained from seismological bulletins; the original records were not examined by the investigator in most cases. The percentage of inconsistent readings is rather high.

Lazareva and Misharina [1965] performed a similar analysis for 15 earthquakes along the continuation of the mid-oceanic seismic belt into the arctic basin and northern Siberia. Most of the solutions were predominantly of a strike-slip nature. Although the inferred axes of maximum tension were approximately perpendicular to the ridge in the Greenland Sea, the inferred axis of maximum compression occupies a similar position in the arctic basin and in northern Siberia. *Scheidegger* [1966] reached similar conclusions from a statistical analysis of the results of Lazareva and Misharina.

Stauder and Bollinger [1964*a*, *b*; 1965] used data from the WWSSN and other stations in an investigation of the larger earthquakes of 1962 and 1963. A combination of data from *P* and *S* waves was employed in their solutions. Seven of the earthquakes examined in the present investigation were also studied by Stauder and Bollinger. The percentage of inconsistent *P*-wave readings in their results ranged from 5 to 30% for these seven earthquakes. Their results indicate a predominance of strike-slip motion in five cases and a predominance of normal faulting in another. A seventh event for which only a tentative solution was presented was characterized by a predominance of thrust faulting. *Stefánsson* [1966] found, however, that a foreshock preceded the latter event by a few seconds. Stefánsson's analysis and the results reported in this paper indicate a predominance of strike-slip motion in the main shock.

Stauder and Bollinger [1966] concluded that the inferred axes of maximum tension were approximately normal to the trend of the ridge. They apparently failed to realize, however, that in each of the solutions dominated by strike-slip motion the epicenter was located on a fracture zone and one of the two nodal planes for *P* waves nearly coincides with the strike of the fracture zone. Stauder and Bollinger's analysis indicated that all their solutions were of the double-couple type; hence, from *P*- and *S*-wave data alone it would not be possible to choose which of the two nodal planes was the fault plane.

Several of the strike-slip solutions of *Stauder and Bollinger* [1966] are in agreement with the sense of motion predicted by *Wilson* [1965*a, b*] for transform faults. Unfortunately, a full test of the hypothesis is not possible with these data, since all the solutions for the mid-oceanic ridges were of the dextral transform type (Figure 1).

Stefánsson [1966] conducted an extensive investigation of the focal mechanisms of two shocks on the mid-Atlantic ridge. Amplitude measurements and *P*- and *S*-wave data were in agreement with a double-couple mechanism. For his best solution only 2 of 85 stations were inconsistent with a quadrant distribution of first motions. *Sutton and Berg* [1958*a*] examined the distribution of first motions for earthquakes in the western rift valley of East Africa. Although the data were not extensive enough to give a unique determination of the predominant type of faulting, the first motions were consistent either with dip-slip faulting on steeply dipping planes parallel to known faults or with strike-slip faulting along near-vertical faults with the eastern sides moving north.

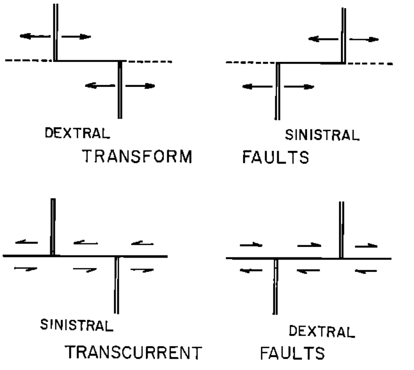

Fig. 1. Sense of motion associated with transform faults and transcurrent faults [after *Wilson*, 1965*a*]. Double line represents crest of mid-oceanic ridge; single line, fracture zone. The terms 'dextral' and 'sinistral' describe the sense of motion of the fracture zones; for the transform faults they do not denote the relative configuration of the two segments of ridge on either side of the fracture zone.

Analysis of Data

Data used. In this investigation first motions of the phases *P* and *PKP* were examined for 17 earthquakes that occurred between March 1962 and March 1966. Epicentral and other pertinent data are listed in Table 1. Reliable solutions probably could be obtained for several additional earthquakes on the mid-oceanic ridges, the west Chile and Macquarie ridges, and the seismically active zone that extends from the Azores to Gibraltar. However, with the exception of one earthquake on the Macquarie ridge emphasis in this paper was placed on an analysis of earthquakes on features that are more generally accepted as mid-oceanic ridges.

Seismograms used in this study were supplied by the World-Wide Standardized Seismograph Network, the Canadian network, and about twenty stations that operate long-period seismographs in cooperation with the Lamont Geological Observatory. The geographical distribution of stations is generally more complete for earthquakes that occurred after 1962.

Reliability of data. An important factor in the use of these new data is the availability of seismograph records. All the readings used in this study were made by the author. A better distribution of stations both in distance and in azimuth can now be obtained with the long-period seismographs in the three networks. Because the networks have a greater sensitivity to small earthquakes, reliable solutions can be determined for a large number of earthquakes with magnitudes as small as about 6. This is an

Table 1. Summary of Earthquake Locations and Other Pertinent Data

Event Number	Figure Number	Region	Latitude	Longitude	Date	Origin Time h	m	s	Magnitude*
1	5	Romanche fracture zone, equatorial Atlantic	00.17°S	18.70°W	Nov. 15, 1965	11	18	46.8	5.6
2	6	Equatorial Atlantic, fracture zone 'Z' of *Heezen, Gerard, and Tharp* [1964]	07.45°N	35.82°W	Aug. 3, 1963	10	21	30.4	6.1
3	7	Equatorial Atlantic, fracture zone 'Z' of *Heezen, Gerard, and Tharp* [1964]	07.80°N	37.35°W	Nov. 17, 1963	00	47	58.8	5.9
4	8	Vema fracture zone, equatorial Atlantic	10.77°N	43.30°W	March 17, 1962	20	47	33.4	
5	10	North Atlantic unnamed fracture zone	23.87°N	45 96°W	May 19, 1963	21	35	45.4	6.0
6	11	North Atlantic	31.03°N	41.49°W	Nov. 16, 1965	15	24	40.8	6.0
7	12	North Atlantic	32 26°N	41.03°W	Aug. 6, 1962	01	35	27.7	
8	13	North Atlantic unnamed fracture zone	35.29°N	36.07°W	May 17, 1964	19	26	16.4	5.6
9	14	Off north coast of Iceland unnamed fracture zone	66.29°N	19.78°W	March 28, 1963	00	15	46.2	
10	16	Laptev Sea, near arctic shelf of Siberia	78.12°N	126.64°E	Aug. 25, 1964	13	47	13.8	6.1
11	18	Lake Kariba, Southern Rhodesia	16.64°S	28.55°E	Sept. 23, 1963	09	01	51.1	5.8
12		Lake Kariba, Southern Rhodesia	16.70°S	28.57°E	Sept. 25, 1963	07	03	48.8	5.8
13	19	Western rift, East Africa	00.81°N	29.93°E	March 20, 1966	01	42	46.8	6.1
14	20	Rivera fracture zone, east Pacific rise	18.87°N	107.18°W	Dec. 6, 1965	11	34	48.9	5.9
15	22	Easter fracture zone, east Pacific rise	26.87°S	113.58°W	March 7, 1963	05	21	56 6	
16	23	Eltanin fracture zone, east Pacific rise	55.35°S	128.24°W	April 3, 1963	14	47	50 4	5 8
17	24	Macquarie ridge, south of New Zealand	49.05°S	164.26°E	Sept. 12, 1964	22	06	58.5	6 9

* Body-wave magnitude, U. S. Coast and Geodetic Survey. All computations for focal depth of 0 km, except event 4 for which depth taken as 31 km.

important factor in investigations of earthquakes on the mid-oceanic ridges, since an event of magnitude 7 occurs in these regions only about once during a period of a few years.

First motions of the *P* phase are usually more reliable on the long-period records. The example in Figure 2, although not typical of all long- and short-period readings, illustrates that in a number of instances the quality of first-motion data is considerably better on the long-period seismograms. Most of the first motions used in this paper were read from long-period records; short-period data were employed only when other records were not available and when the sense of first motion was clearly evident. For earthquakes of magnitude near 6 the response of the long-period instruments is such that the recorded signals approximate those from a point source. A point source is probably not a good approximation for waves of periods between 0.5 and 2 sec.

In addition to the factors already mentioned, the calibration and polarity of the WWSSN stations are better known. In this study the number of inconsistent readings of first motion is less than 1%. In many previous investigations 15 to 20% of the data were often inconsistent with the inferred quadrant distribution of first motion [*Hodgson and Adams*, 1958].

The reliability of the long-period networks is such that readings from stations with polarity reversals are clearly indicated. In this study and in an investigation of earthquake mechanisms for the southwest Pacific [*Isacks et al.*, 1967] the four stations GIE, PEL, TAU, and PHC consistently exhibited first motions that were inconsistent with determinations from other nearby stations. These reversals were confirmed by the Seismology Data Center of the WWSSN for the first three stations; the polarity reversals were corrected during maintenance visits to these stations (T. A. Modgling, personal communication). These reversals were taken into account in the presentation of the data in this paper.

Method of projection. An equal-area projection [*Friedman,* 1964] of the lower hemisphere of the focal sphere was used throughout this investigation. The two coordinates used to describe a point are the azimuth of the station at the epicenter and the radial distance R, where R is proportional to $\sqrt{2} \cdot \sin (i/2)$ and i is the angle of incidence at the source as measured from the downward vertical.

Values of i for a given distance and depth were computed from the tables of *Hodgson and Storey* [1953] and *Hodgson and Allen* [1954]. The assumed values of i may be in error because the tables do not make allowance for velocities at the focus that are less than about 7.8 km/sec [*Romney,* 1957; *Sutton and Berg,* 1958*b*]. Nevertheless, since the computed depths of the earthquakes in this study may be uncertain by as much as 50 km, a more complex model for the velocity distribution did not seem to be justified at the present time. Mechanism solutions that represent a predominance of strike-slip motion on steeply dipping faults are not influenced significantly by these uncertainties. Solutions representing a predominance of dip-slip motion on faults of dip less than about 60°, however, may be affected to a much greater extent. Nonetheless, for the latter class of solutions the principal point made in this paper is that a large dip-slip component did, in fact, exist.

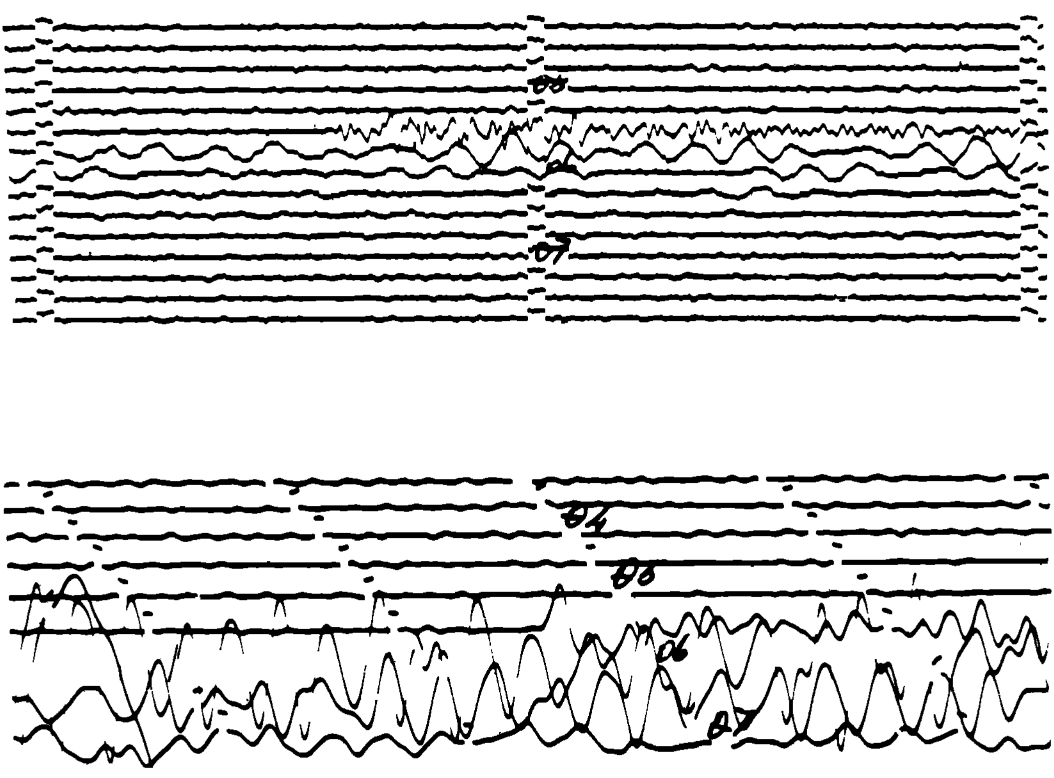

Fig. 2. Comparison of first motions on short-period vertical component (*above*) and long-period vertical component (*below*) at Arequipa, Peru, for earthquake of March 7, 1963 (event 15 in Table 1). P wave arrived at 05 h 59m. First motion is uncertain on the short-period record but is clearly compressional (upward motion on record) on the long-period seismogram. Deflections of trace occur once per minute.

Transform and Transcurrent Faults

Wilson [1965*a, b*] has recently proposed a separate class of horizontal shear faults—the transform fault. Dextral and sinistral transform faults of the ridge-ridge type and their transcurrent counterparts are illustrated in Figure 1. In the transcurrent models it is tacitly assumed that the faulted medium is continuous and conserved, whereas in the transform hypothesis the ridges expand to produce new crust [*Wilson*, 1965*a*]. Thus, a transform fault may terminate abruptly at both ends even though great displacements may have occurred either on the central portions of the fracture zone or, at some time in the past, on portions of the fault that are no longer located between the two ridge crests (Figure 1, dashed segments).

Another significant difference noted by *Wilson* [1965*a*] was that the motion on transform faults (upper half Figure 1) is the reverse of the motion required to offset the ridge (lower half Figure 1). Also present seismicity should be largely confined to the region between the ridge crests for transform faulting but should not exhibit such an abrupt decrease for transcurrent faulting.

In this paper the term 'fault plane' is used to describe a zone of shear displacement or shear dislocation. No attempt is made to define the physical mechanism of deformation more specifically.

Presentation of Data for the Mid-Oceanic Ridges

Figure 3 illustrates the locations of the 17 earthquakes for which mechanism solutions were obtained. The numbers beside the epicenters refer to the data in Table 1. Events 1 through 9 are located on the mid-Atlantic ridge, earthquake 10 is on the extension of the mid-oceanic ridge system in the Arctic, events 11 through 13 are in East Africa, 14 through 16 are on the east Pacific rise, and event 17 is on the Macquarie ridge.

Equatorial Atlantic

Fracture zones. Between 15°N and 5°S the crest of the mid-Atlantic ridge is displaced to the east a total of nearly 35° (Figure 4). The

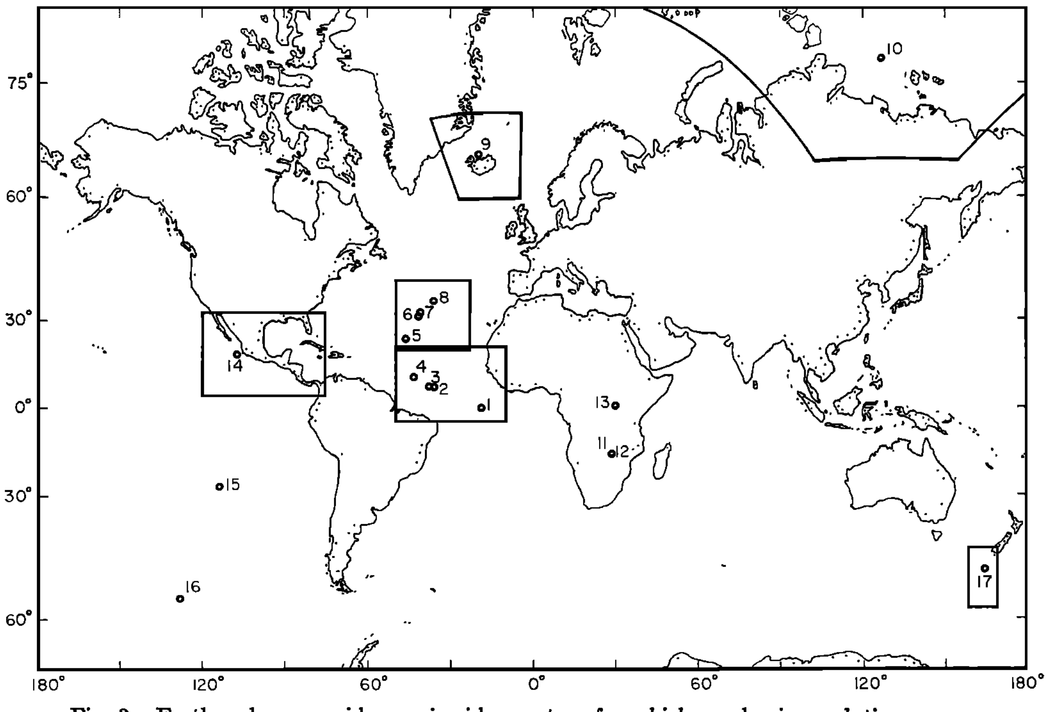

Fig. 3. Earthquakes on mid-oceanic ridge system for which mechanism solutions are presented in this paper. Numbers beside epicenters refer to designations and data in Table 1. Inserts denote areas that are shown in greater detail in Figures 4, 9, 15, 17, 21, and 25.

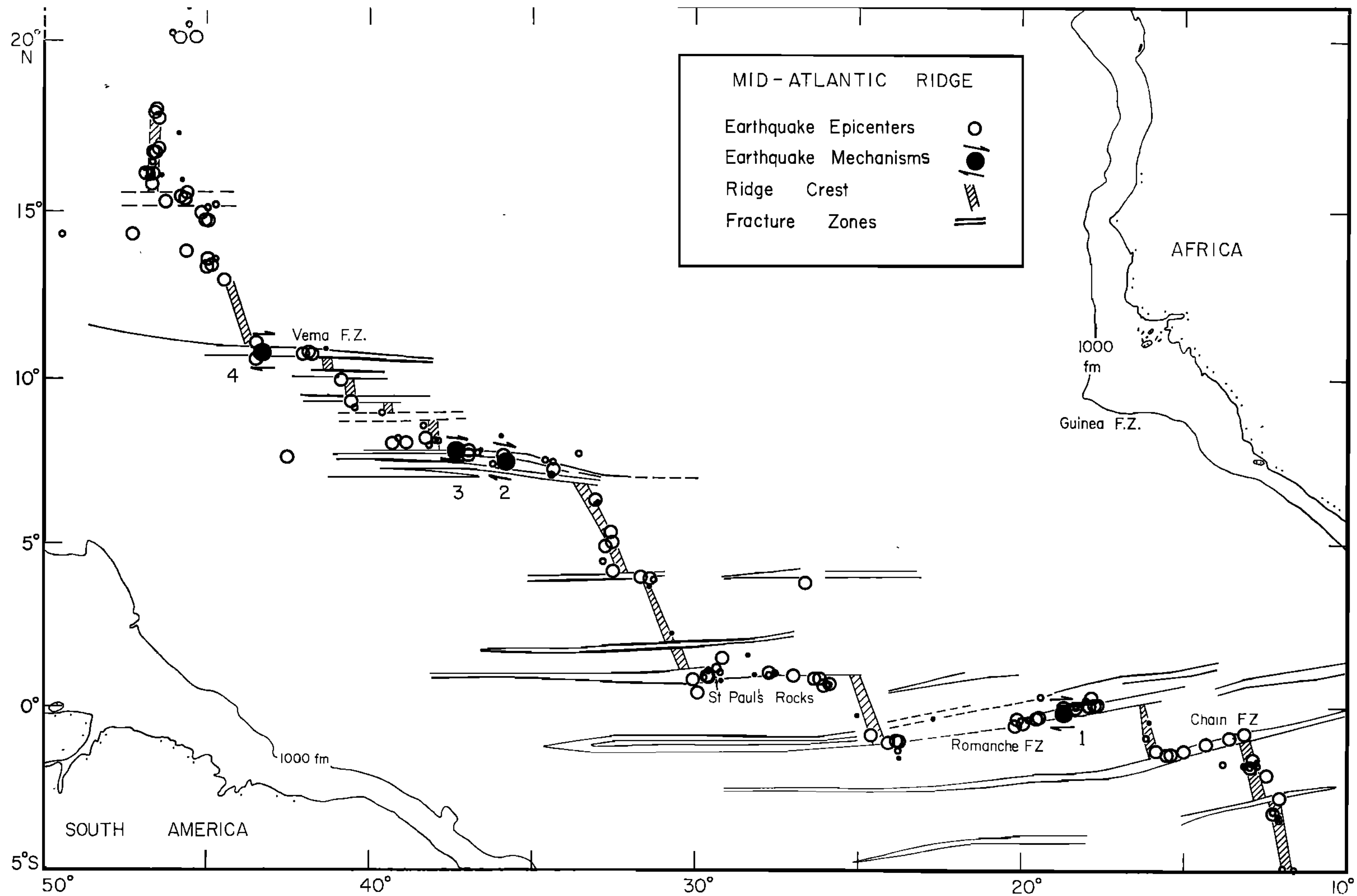

Fig. 4. Relocated epicenters of earthquakes (1955–1965) and mechanism solutions for four earthquakes along the equatorial portion of the mid-Atlantic ridge. Ridge crests and fracture zones from *Heezen, Bunce, Hersey, and Tharp* [1964] and *Heezen, Gerard, and Tharp* [1964]. Sense of shear displacement and strike of inferred fault plane are indicated by the orientation of the set of arrows beside each mechanism. Numbers beside mechanism solutions refer to data in Table 1. Large circles denote more precise epicentral determinations; smaller circles, poorer determinations.

apparent displacement is such that the ridge crest maintains its median character throughout the North and South Atlantic oceans. *Hess* [1955] identified the Romanche trench (near event 1 in Figure 4) as a part of a major fracture zone and noted that St. Paul's Rocks appear to be located at the western end of a great fault scarp. *Heezen and Tharp* [1961], *Heezen, Bunce, Hersey, and Tharp* [1964], and *Heezen, Gerard, and Tharp* [1964] more recently identified a whole series of fracture zones in the equatorial Atlantic (Figure 4). *Heezen and Tharp* [1965*b*] concluded that in this area the ridge crest had been offset by sinistral transcurrent faults. They noted that the fracture zones appeared to be parallel to inferred flow lines for the continental drift of Africa relative to South America.

Seismicity of the equatorial Atlantic. Earthquake epicenters in the equatorial Atlantic were relocated for the period 1955 to 1965; the results are presented in Figure 4. The methods and computer programs used in these relocations were similar to those described in previous seismicity studies [*Sykes,* 1963, 1965, 1966; *Sykes and Ewing,* 1965; *Sykes and Landisman,* 1964; *Tobin and Sykes,* 1966].

The distribution of earthquakes is similar to that found in other portions of the mid-oceanic ridge [*Sykes,* 1963, 1965]—nearly all the activity on each fracture zone is confined to the region between the ridge crests. This is particularly well illustrated for the Chain fracture zone near 1°S, 15°W. The distribution of epicenters also shows that *Heezen and Tharp's* [1961, 1965] interpretations of the pattern of ridges and fracture zones are largely correct. Although a few earthquakes are found on other portions of fracture zones, the number is relatively small. The abrupt cessation of activity at the ridge crests appears to be a strong argument for the transform-fault hypothesis.

Menard [1965] stated that several fracture zones are active far out on the flanks of oceanic rises. As examples he cited the west Chile ridge, an active zone that extends from the Azores to Gibraltar, and a few additional epicenters on fracture zones. Nonetheless, the important generalization from this and other seismicity studies seems to be that on *most* fracture zones *most* of the activity is confined to the region between the two ridge crests. On the contrary, seismic activity between the Azores and Gibraltar and on the Macquarie and west Chile ridges suggests that at the present time these features are quite different from most of the fracture zones of the mid-oceanic ridge. Investigations of the mechanism of earthquakes and analyses of magnetic anomalies should provide more definitive information about these more unusual features. A small amount of differential spreading on the two sides of a fracture zone could account for the isolated earthquakes that occur off the ridge crest on fracture zones. In any case the seismicity of the basins on either side of the ridge appears to be extremely low.

Most of the seismic activity that is associated with fracture zones and with the crest of the ridge is confined to remarkably narrow zones. In some cases these active zones are less than 20 km wide. In contrast, activity along continental extensions of the mid-oceanic ridges usually exhibits a greater areal scatter [*Sykes and Landisman,* 1964; *Sykes,* 1965]. Likewise, in California the epicenters of earthquakes smaller than magnitude 6 are also scattered throughout a zone more than 200 km wide [*Richter,* 1958; *Allen et al.,* 1965]. Hence, the pattern of seismic dislocations appears to be extremely simple in most of the oceanic portions of the ridge system. Analyses of earthquake periodicities in time and in space and investigations of triggering mechanisms might yield more interesting results if a relatively simple system such as that associated with a particular fracture zone were analyzed. Many of the larger earthquakes listed by *Gutenberg and Richter* [1954] for the mid-Atlantic ridge are located on or near major fracture zones.

Strike-slip mechanisms. Mechanism solutions for four earthquakes that were located on equatorial fracture zones are presented in Figures 5 through 8. Solid circles denote compressions; open circles, dilatations. When long-period records were available, it was often possible to tell from the size of the *P* wave relative to that of other phases whether the station was in the vicinity of one of the two nodal planes. Arrivals of this type are denoted by a cross on the figures. As an examination of the figures reveals, these arrivals are often a good qualitative indication that the station was near a nodal plane. Even when the first motion of such a signal cannot be ascertained, this information is an

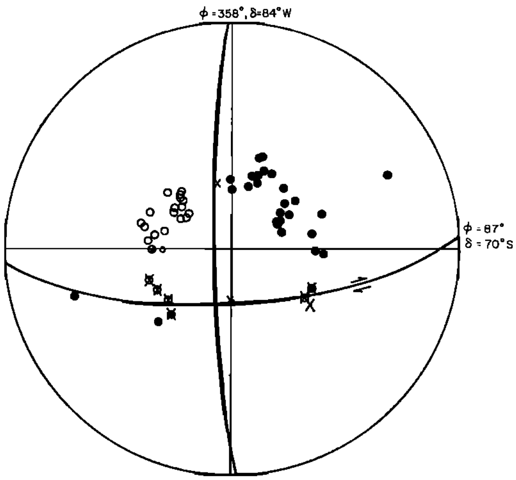

Fig. 5. Mechanism determination for the shock of November 15, 1965, on the mid-Atlantic ridge (event 1 in Table 1 and in Figures 3 and 4). Diagram is an equal-area projection of the lower hemisphere of the radiation field. Solid circles represent compressions; open circles, dilatations; crosses, wave character on seismograms, indicating station is near nodal plane. Smaller symbols represent poorer data. ϕ and δ are strike and dip of the nodal planes. Arrows indicate sense of shear displacement on the plane that was chosen as the fault plane,

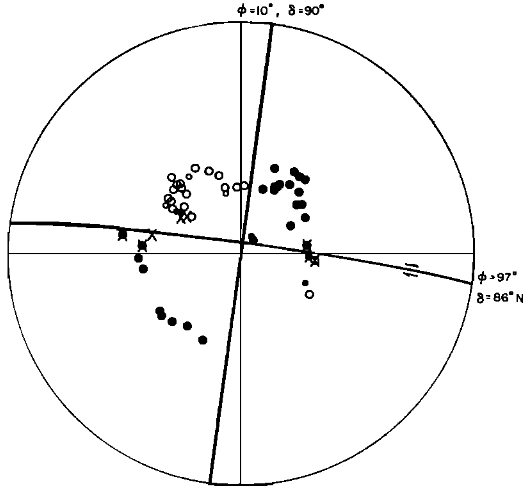

Fig. 7. Mechanism solution for event 3. Table 1 and Figures 3 and 4 give position and other pertinent data. Symbols same as Figure 5. *Note added in proof:* Strikes of two planes should read 8° and 98° rather than 10° and 97°.

additional constraint on the orientation of the nodal planes.

A quadrant distribution of first motions seems to be an excellent approximation to the data in Figures 5 through 8. Only four readings are inconsistent with this interpretation. Seismograms from these four stations are of marginal quality and should not be taken as evidence against a quadrant distribution.

In each of the four cases illustrated in these figures one nodal plane strikes approximately east and the other strikes nearly north. From analyses of the polarization of the S waves for several shocks on the mid-oceanic ridge *Stauder*

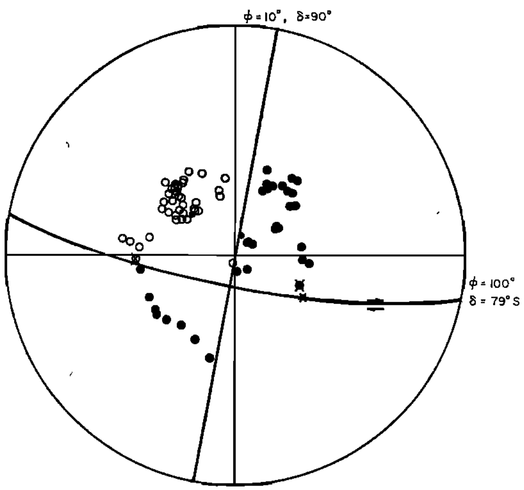

Fig. 6. Mechanism solution for event 2. Table 1 and Figures 3 and 4 give epicentral and other pertinent data. Symbols same as Figure 5.

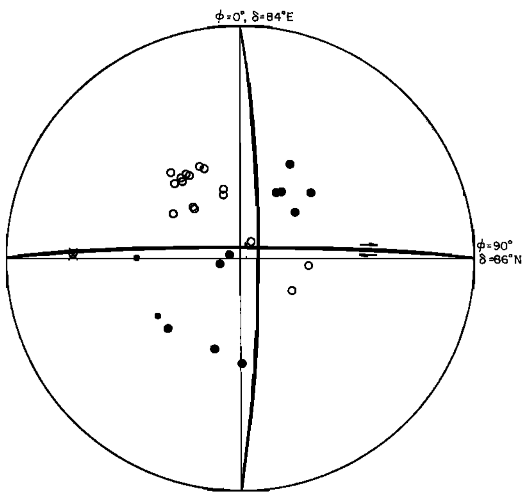

Fig. 8. Mechanism solution for event 4. Table 1 and Figures 3 and 4 contain position and other pertinent data. Symbols same as Figure 5.

and Bollinger [1966] showed that the mechanisms are of the double-couple type. Thus, *S* waves do not furnish criteria for chosing which of the two nodal planes is the fault plane. In each of these four cases the choice is between a predominance of dextral strike-slip motion on a steeply dipping plane that strikes approximately east or a predominance of sinistral strike-slip motion on a steeply dipping plane that strikes nearly north.

Choice of the fault plane. Although a unique choice of the fault plane cannot be made from the first motion data or from an analysis of *S* waves, the east-striking plane seems to be overwhelmingly favored for the following reasons:

1. For each earthquake the epicenter is located on a prominent fracture zone; the strike of one of the two nodal planes nearly coincides with the strike of the fracture zone (Figure 4).
2. Earthquake epicenters are aligned along the strike of the fracture zones.
3. The linearity of fracture zones suggests a strike-slip origin [*Menard,* 1965]. The bathymetry and other morphological aspects are similar to the morphology of the great strike-slip fault zones on continents.
4. Many of the rocks from St. Paul's Rocks (Figure 4) are described as dunite-mylonites [*Washington,* 1930*a*, *b*; *Tilley,* 1947; *Wiseman,* 1966]. Rocks dredged from other fracture zones [*Shand,* 1949; *Tolstoy* 1951; *Quon and Ehlers,* 1963], as well as samples from cores taken in fracture zones [*Heezen, Bunce, Hersey, and Tharp,* 1964], exhibit a similar petrology and provide evidence for intense shearing stresses in the vicinity of fracture zones.
5. The choice of the north-striking plane would indicate strike-slip motion nearly parallel to the ridge axis. On the contrary, earthquakes on the ridge axis but not on fracture zones are characterized by a predominance of normal faulting.
6. If the east-striking plane is chosen, the sense of relative motion on the fracture zone reverses when the apparent offset of the crests of the ridge is interchanged (Figure 1).

Agreement with strike of fracture zones. Figure 4 demonstrates that the observed strike of one of the two nodal planes agrees very closely with the trend of the fracture zones on which the earthquakes occurred. *Heezen, Bunce, Hersey, and Tharp* [1964] report that the over-all trend of the Romanche trench (a fault trough in the Romanche fracture zone) is about 80°. The strike determined for event 1, an earthquake that occurred in the trench, is about 87°. Fortunately, in this solution and in the other solutions for the mid-Atlantic ridge the east-striking nodal plane can be estimated with greater precision than the north-striking plane. The discrepancy between the two strikes could be explained by variations in the strikes of the individual fractures in the trench or by uncertainties in the determination of the mechanism.

Events 2 and 3 are both located on a large fracture zone near 8°N; their mechanisms appear to be very similar. The Guinea fracture zone near 9°N, 16°W (Figure 4) may represent the eastward continuation of this fracture zone rather than the continuation of the Vema fracture zone (near 11°N, 43°W) as *Krause* [1964] suggested. Wilson [1965*a*] suggested that the offsets of the crest of the ridge are a reflection of the shape of the initial break between the continental blocks of Africa and South America. The pattern of ridges and fracture zones between 8°N and 1°S appears to match the configuration of the African coast (or the shape of the continental slope) between 9°N and 2°N.

North Atlantic

Figure 9 indicates the locations of four mechanism determinations for the mid-Atlantic ridge in the North Atlantic. The mechanisms are indicated in Figures 10 through 13. Relocated epicenters for the period 1955 to 1965 are also shown in Figure 9. Two of the solutions are characterized by a predominance of strike-slip motion on steeply dipping planes; the others are characterized by a large component of normal faulting.

Strike-slip mechanisms. The observed radiation field for event 5 (Figures 9 and 10) is similar to that for events 1 through 4. The pattern of epicenters near 24°N and the observed mechanism for event 5 are indicative of a dextral transform fault. Nearly all the first motions observed for event 8 (Figure 13), however, are opposite in sense to those observed for events 1 through 5. The over-all strike of the

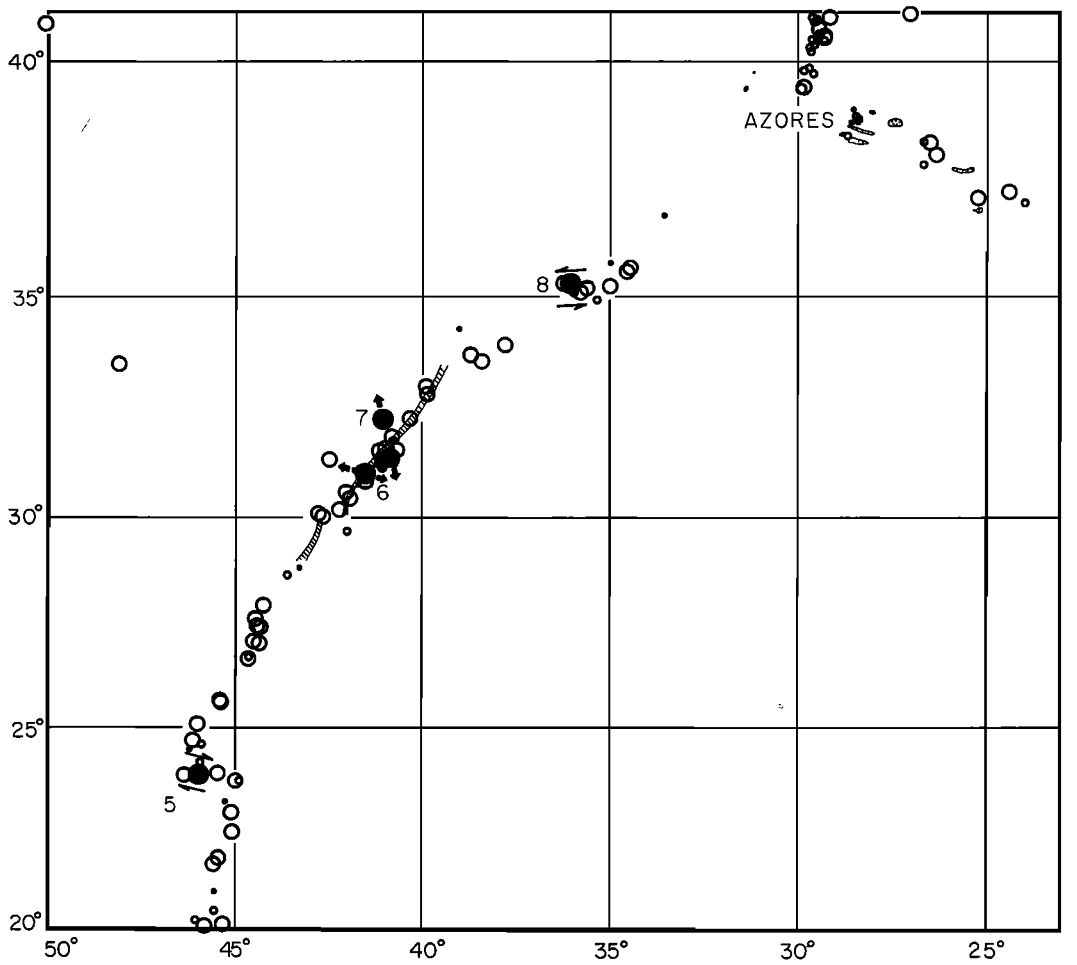

Fig. 9. Relocated epicenters of earthquakes (1955–1965) and mechanism solutions for four earthquakes along a portion of the mid-Atlantic ridge. Rift valley in mid-Atlantic ridge is denoted by diagonal hatching and is from *Heezen and Tharp* [1965b]. Other symbols same as Figure 4. For events 6 and 7 thick arrows denote inferred axes of maximum tension.

ridge does not appear to change appreciably between events 5 and 8. The east–west alignment of epicenters near 35°N, the bathymetry in this region [*Tolstoy and Ewing,* 1949; *Tolstoy,* 1951; *Heezen et al.,* 1959], and the mechanism of event 8 are indicative of a sinistral transform fault that strikes approximately east. *Heezen and Ewing* [1963] indicated a major fracture zone on the ridge near 33°N. The configuration of the two ridge crests and the distribution of epicenters suggest that this fracture zone is also a sinistral transform fault.

Normal faults. Solutions for events 6 and 7 (Figures 11 and 12) display an entirely different pattern of first motions; all the more distant stations recorded dilatations. The inferred solutions are characterized by a large component of normal-fault motion on planes that strike approximately parallel to the axis of the ridge. Although a fracture zone has been mapped near 30.0°N [*Tolstoy and Ewing,* 1949; *Tolstoy,* 1951; *Heezen and Tharp,* 1965b], no major fracture zones seem to intersect the ridge near events 6 and 7. In this region the position of the rift valley was mapped with enough precision so that offsets greater than a few tens of kilometers should have been resolvable.

Talwani [1964] suggested that all earthquakes

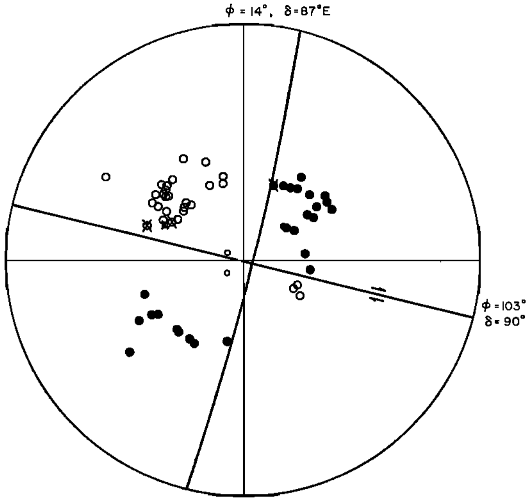

Fig. 10. Mechanism solution for event 5. Table 1 and Figures 3 and 9 contain position and other pertinent data. Symbols same as Figure 5.

on the mid-oceanic ridge may be related to fracture zones that are not prominent enough to have been detected yet on the basis of bathymetry. The existence of two types of earthquake mechanisms suggests, however, that this is not the case. *Heirtzler et al.* [1966] concluded that, although earthquakes have been detected south

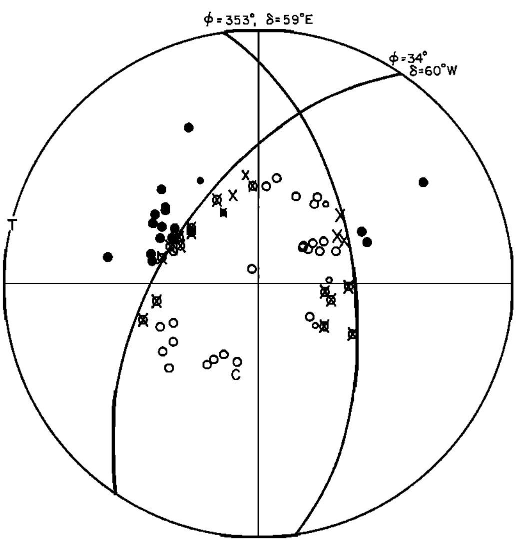

Fig. 11. Mechanism solution for event 6. Table 1 and Figures 3 and 9 give epicentral and other data. *T* and *C* are inferred axes of maximum tension and compression, respectively. Other symbols same as Figure 5.

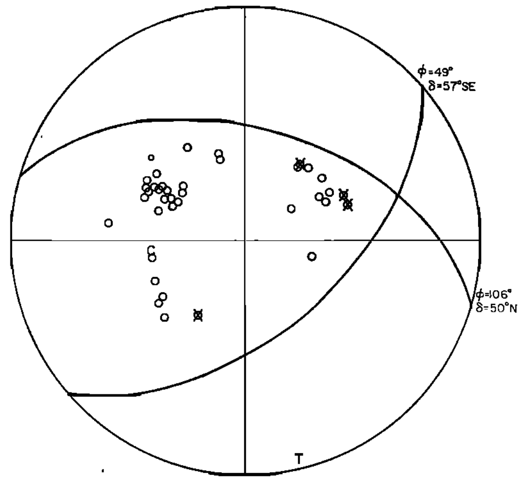

Fig. 12. Mechanism solution for event 7. Table 1 and Figures 3 and 9 give epicentral and other data. Other symbols same as Figures 5 and 11.

of Iceland on the Reykjanes ridge [*Sykes*, 1965], there is no bathymetric or magnetic evidence for offsets of the ridge between 60°N and 63°N.

Inferred axis of maximum tension. The directions of principal stress difference were estimated by assuming that these directions bisect the angle between the nodal planes and are located in a plane perpendicular to the two nodal planes. This approximation is probably sufficiently accurate for the purposes of the

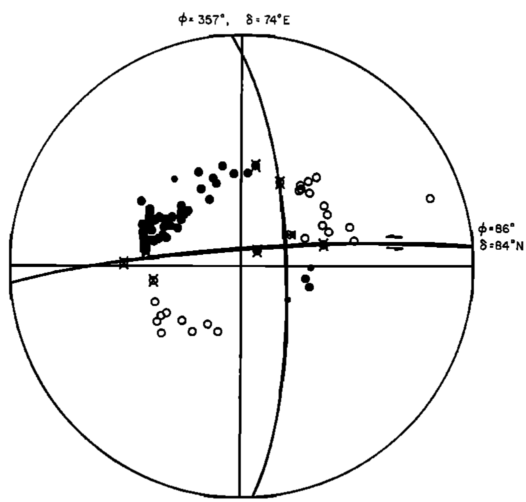

Fig. 13. Mechanism solution for event 8. Table 1 and Figures 3 and 9 contain epicentral and other pertinent data. Symbols same as Figure 5.

discussion in this paper. The term 'maximum tension' as used in this discussion refers to the state of stress relative to a constant mean normal stress (hydrostatic pressure). The inferred axes of maximum tension for events 6 and 7 are nearly horizontal and are approximately perpendicular to the local strike of the ridge. The orientation of these planes for event 7 (Figure 12) may be in error by several tens of degrees. For each of the earthquakes examined in this study the pattern of first motions is similar to that predicted for a shear displacement. Radiation patterns that resemble those calculated for extension fractures [*Honda,* 1962; *Savage,* 1965] were not observed.

Iceland and Jan Mayen

First-motion data for the Icelandic earthquake of March 28, 1963, are shown in Figure 14. Epicenters near this shock (Figure 15) and the configuration of the zone of postglacial volcanic activity suggest that this earthquake occurred near the western end of a dextral transform fault. The mechanism for this earthquake is in agreement with this interpretation.

The bathymetry and the pattern of epicenters [*Sykes,* 1965] indicate that a major fracture zone striking nearly east is present near the island of Jan Mayen (Figure 15). Since no large earthquakes occurred on this fracture zone during the period 1962 to 1965, data from the WWSSN could not be used to investigate this feature. Solutions presented by *Lazareva and Misharina* [1965] suggest that the fracture zone is of the sinistral transform type.

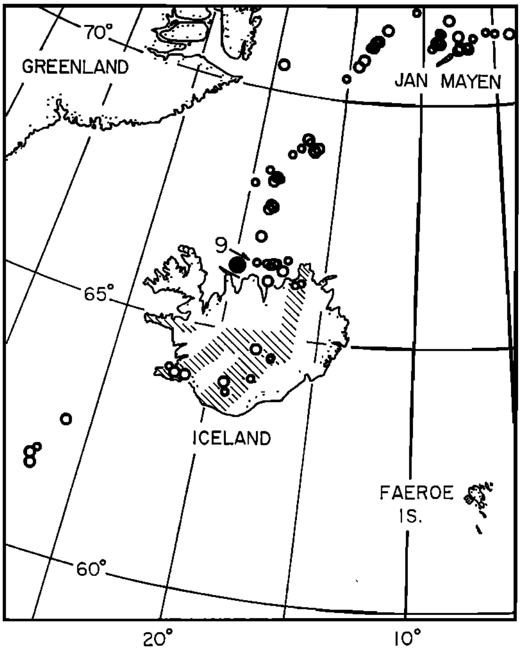

Fig. 15. Relocated epicenters of earthquakes along a portion of the mid-Atlantic ridge near Iceland [after *Sykes,* 1965]. Diagonal hatching denotes regions of postglacial volcanic activity in Iceland [after *Bodvarsson and Walker,* 1964]. Other symbols same as Figure 4.

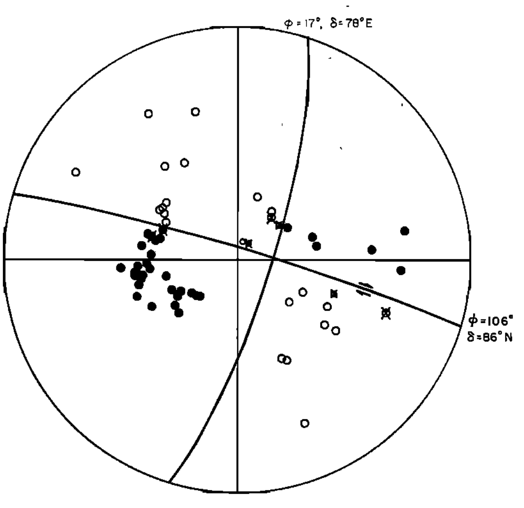

Fig. 14. Mechanism solution for Icelandic earthquake of March 28, 1963 (event 9 in Table 1). Location of earthquake is illustrated in Figures 3 and 15.

Extensions of the Mid-Oceanic Ridge

Arctic Extension

Event 10, which is located near the edge of the continental shelf of northern Eurasia, is characterized by a large component of normal faulting (Figure 16). The epicenter of this event is located on the extension of the mid-oceanic ridge system into the Arctic basin and into northern Siberia (Figure 17). The seismic zone [*Sykes,* 1965], which is believed to define the crest of the ridge in this region, is nearly perpendicular to the inferred axis of maximum tension.

Balakina et al. [1960] reported that earthquakes in northeastern and central Prebaikalye (the region south of the area shown in Figure 17) are also characterized by a large compo-

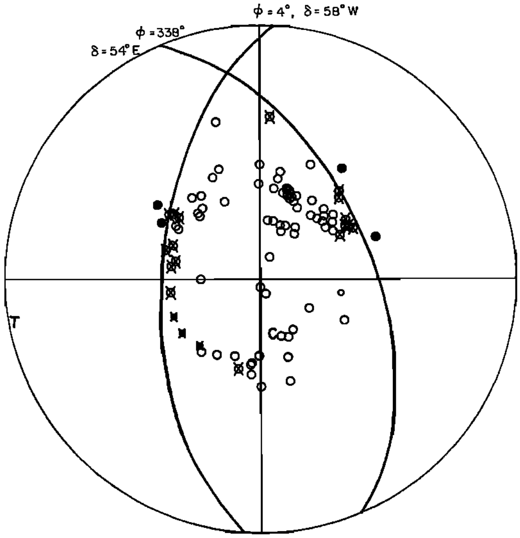

Fig. 16. Mechanism solution for earthquake (event 10) near the continental shelf of northern Siberia. Symbols same as Figures 5 and 11. Location of event shown in Figures 3 and 17.

nent of normal faulting. Nevertheless, *Lazareva and Misharina* [1965] found that earthquakes in the area shown in Figure 17 are characterized by a predominance of strike-slip faulting and that the inferred axes of maximum compression are approximately perpendicular to the trend of the ridge. Many of these solutions are based on a rather poor distribution of stations, and a relatively large number of the observations are inconsistent with the inferred mechanisms. Solutions based on a poor distribution of stations and on poor data may be biased so that the computed displacements appear to be largely strike-slip [*Adams*, 1963; *Ritsema*, 1964; *Isacks et al.*, 1967]. In this paper the distribution of stations in distance and azimuth is more extensive. Relatively little difficulty was encountered in distinguishing dip-slip from strike-slip motion. Until other high-quality solutions are available it does not seem possible to ascertain whether faulting in the Arctic is predominantly strike-slip faulting, normal faulting, or, as *Wilson* [1965*a*] suggests, a combination of extensional tectonics in the arctic basin and compressional tectonics in the Verkhoyansk mountains.

Orthogonality criterion. In most experimental studies of earthquake mechanisms it is assumed that the two nodal planes are orthogonal. Even with some of the best published data it is not possible, however, to state that the two nodal planes are orthogonal with a precision better than about 10° or 20°. Data for events 6 and 10 (Figures 11 and 16) are extensive enough so that the validity of the orthogonality criterion may be tested. The fewest inconsistencies were encountered when the dilatational quadrants subtended an angle of about 70°. The use of a velocity model more appropriate for crustal earthquakes would result in a somewhat smaller angle. Nevertheless, orthogonal nodal planes would not violate very many of the data for these two examples, and the case for nonorthogonal solutions does not seem to be established with certainty. The other solutions in this paper were fitted with orthogonal nodal planes. An angle of 70° between the dilatational quadrants would also satisfy the observations equally well. This uncertainty, however, mainly affects the orientation of the north-striking plane for the solutions characterized by a predominance of strike-slip motion; the orientation of the east-striking nodal plane, the plane chosen as the fault plane, is not noticeably affected by this uncertainty.

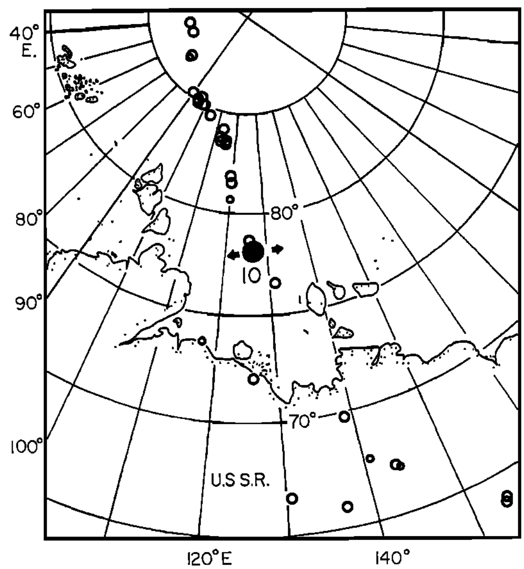

Fig. 17. Epicenters along a portion of the mid-oceanic ridge in the Arctic [after *Sykes*, 1965]. Thick arrows denote inferred axis of maximum tension for event 10. Other symbols same as Figure 4.

East Africa

The mechanisms of three earthquakes in East Africa all indicate a large component of normal faulting (Figures 18 and 19). Since the number of stations in Africa is limited, the position of the two nodal planes cannot be fixed with great precision; a strike-slip component nearly as large as the dip-slip component would still be compatible with the observed data. Studies of shear waves may help to define the mechanisms more precisely.

The inferred axis of maximum tension for event 13, an earthquake in the western rift of East Africa on March 20, 1966, is nearly perpendicular to the strike of the rift in the vicinity of the epicenter. *Wohlenberg* [1966] described fault displacements associated with this earthquake that start at about 0.7°N, 29.8°E and continue for about 40 km in a northerly direction. He reports a vertical displacement of 30 to 40 cm with the western side moving up relative to the eastern side. No horizontal displacement was observed. *Loupekine* [1966] reported a fault break of 15 to 20 km striking NNE. He indicated a throw of 2 meters with the downthrow on the east side. These observations are in close agreement with the inferred mechanism (Figure 19) if the nodal plane that strikes about 14° is chosen as the fault plane. Geological work and drilling in this portion of the western rift [*Davies,* 1951] are strongly indicative of a system of extensional tectonics; no evidence of compression was obtained.

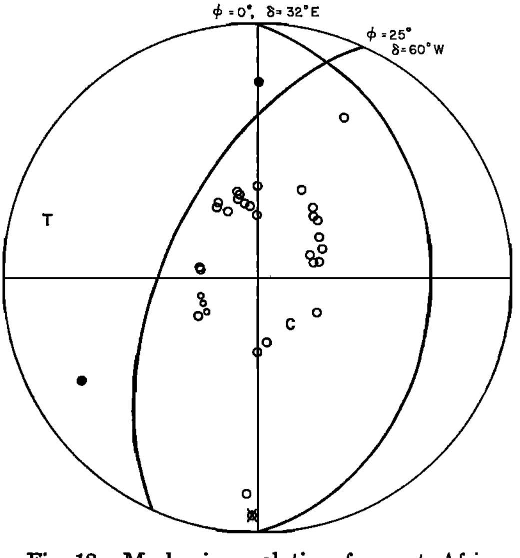

Fig. 18. Mechanism solution for east African earthquake of September 23, 1963 (event 11). Symbols same as Figures 5 and 11. Table 1 and Figure 3 indicate location and other pertinent data. Solution for another earthquake in this swarm (event 12 on September 25, 1963) is nearly identical to that for event 11.

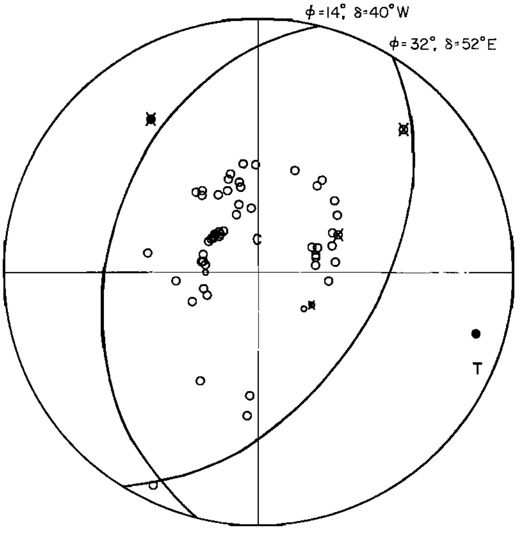

Fig. 19. Mechanism solution for east African earthquake of March 20, 1966 (event 13). Symbols same as Figures 5 and 11; Table 1 and Figure 3 give location and other data.

Events 11 and 12 were part of a swarm of earthquakes that occurred beneath Lake Kariba near the border of Zambia and Rhodesia. The first motions for the two events are identical except that data were not available from two of the close stations for event 12. The inferred state of stress was such that a large water load would have increased the stress difference and hence may have triggered the swarm of earthquakes. *Carder* [1945] described a similar phenomenon in the Hoover Dam area.

Gough and Gough (1962, personal communication) recorded several thousand small earthquakes near Lake Kariba between 1961 and 1963. The large events in September 1963 occurred a few months after the lake reached its maximum level.

East Pacific Rise

General. First-motion data and inferred mechanisms for three earthquakes on the east Pacific rise are shown in Figures 20, 22, and 23.

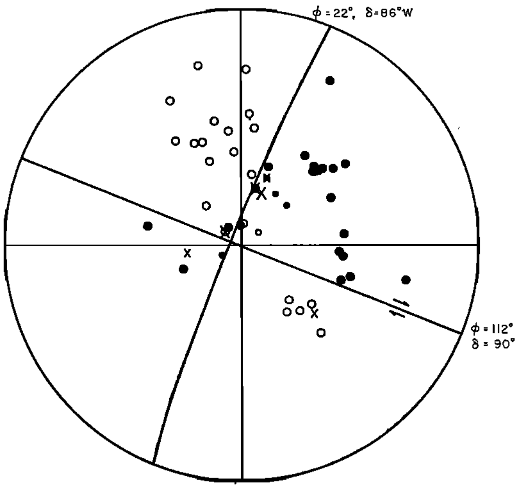

Fig. 20. Mechanism solution for earthquake on the Rivera fracture zone (event 14). Symbols same as Figure 5. Location and other pertinent data shown in Figures 3 and 21 and in Table 1.

All three shocks were located on known fracture zones; the mechanisms are each characterized by a predominance of strike-slip motion. Solutions with a large component of dip slip were not detected on the east Pacific rise. Event 14 was located off the west coast of Mexico on the Rivera fracture zone (Figure 21); event 15 occurred on the Easter fracture zone near 27°S, 114°W. In both cases the inferred mechanisms, the bathymetry [*Menard,* 1966], and the seismicity [*Sykes,* 1963; *Sykes,* 1967] are indicative of dextral transform faults.

Because of its small size and remote location, it was not possible to obtain a unique solution for event 16, an earthquake on the Eltanin fracture zone. If, however, strike-slip faulting on a steeply dipping plane with the same strike as the fracture zone is assumed, the sense of motion can be inferred from the first motions (Figure 23). The bathymetry [*Menard,* 1964], seismicity [*Sykes,* 1963], and mechanism are oriented in the correct sense for a sinistral transform fault.

It is interesting that the pattern of epicenters and the inferred mechanism of an earthquake on the Rivera fracture zone are rotated about 20° to 30° with respect to the strike of the Clarion zone further west (Figure 21). *Menard* [1966] and Chase and Menard (personal communication) have deduced a similar strike for the Rivera fracture zone. The configuration of the active seismic zone and the mechanism for event 14 support *Menard*'s [1966] interpretation that the Rivera zone and the Clarion fracture zone may be distinct tectonic features. Likewise, the Clipperton fracture zone (Figure 21) does not appear to be seismically active for more than a few tens of kilometers near the crest of the east Pacific rise (if at all). The data for the Rivera fracture zone support *Vine*'s [1966] contention that the direction of spreading from the east Pacific rise has changed during the Pliocene from east–west to approximately northwest–southeast.

Recently a system of mid-oceanic ridges and fracture zones has been recognized off the coasts of British Columbia, Washington, Oregon, and northern California [*Menard,* 1964; *Talwani et al.,* 1965; *Wilson,* 1965*b*]. Although no solutions of earthquake mechanisms were made for shocks in this region, an analysis of future events should be of great value in deciphering the tectonic interaction of these features both with one another and with the San Andreas system. A reconsideration of the Mendocino, Murray, and other fracture zones in this region as transform faults could lead to an interpretation wherein the sense of movements inferred for the ocean floor would no longer be the reverse of those observed on land.

Macquarie Ridge. In the previous solutions emphasis was placed on examining data for features that are generally recognized as mid-oceanic ridges or the continental extensions of these ridges. Seismically active features, such as the Macquarie, west Chile, and Azores-Gibraltar ridges, have not been universally interpreted either as mid-oceanic ridges or as fracture zones [*Heezen et al.,* 1959; *Menard,* 1965, 1966].

The inferred mechanism for event 17, an earthquake located on the Macquarie ridge (Figures 24 and 25), is unlike any of the other solutions described in this paper. Although interpretations involving greater or lesser amounts of strike-slip motion than shown in Figure 24 are possible, still a large component of thrust faulting seems to be demanded by the compressional arrivals at the more distant stations.

The inferred compressional axis for this solution is nearly horizontal and is approximately perpendicular to the trend of the Macquarie ridge [*Brodie and Dawson,* 1965] and the strike

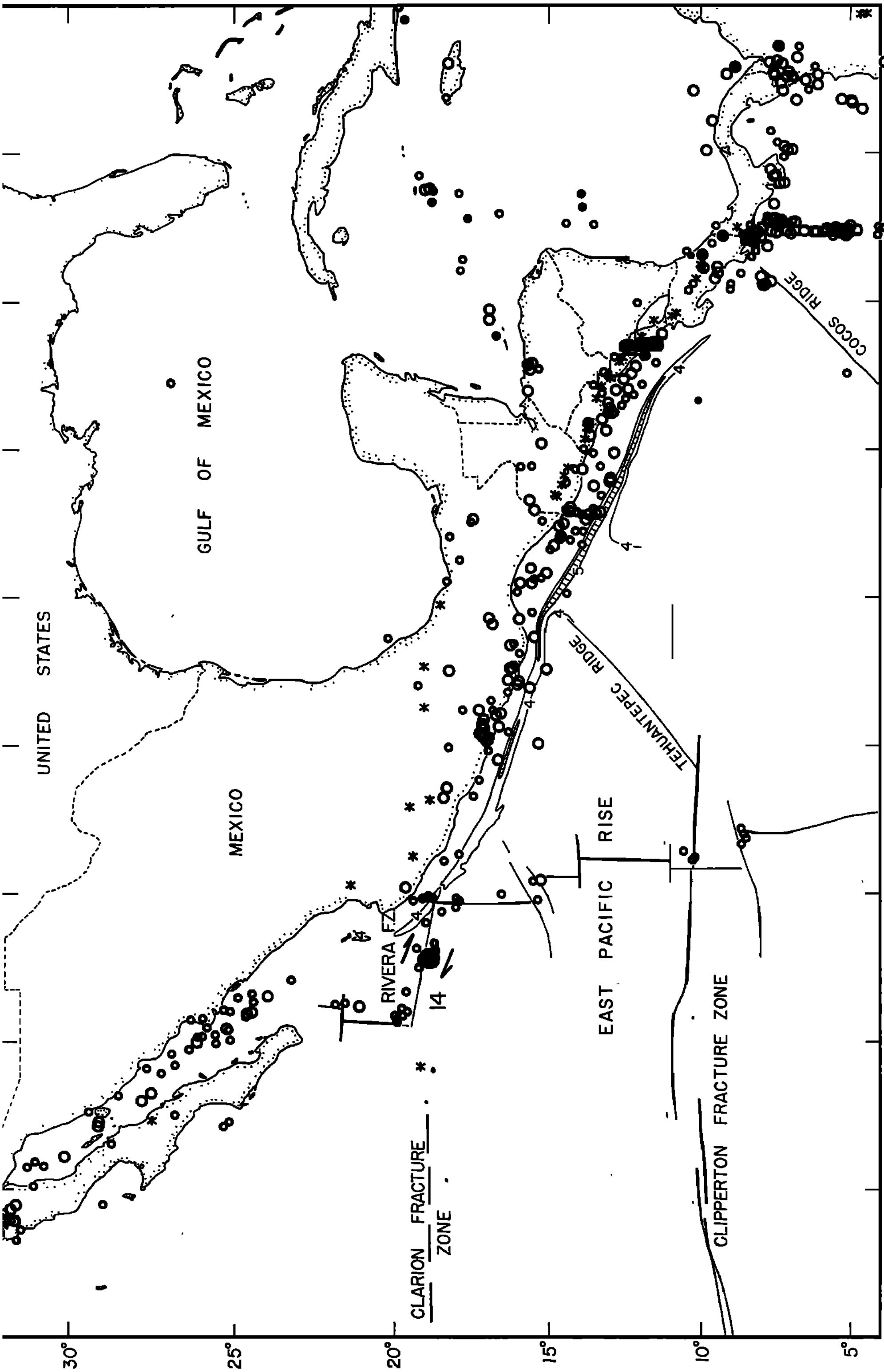

Fig. 21. Epicenters of shallow earthquakes (depth less than about 70 km) in Mexico, Central America, and adjacent oceanic areas for the period 1954–1962 [after *Sykes*, 1967]. Bathymetry of middle America trench after *Fisher* [1961]; water depths in kilometers. Fracture zones and crests of east Pacific rise after *Menard* [1966]. Mechanism solution indicated for event 14 on the Rivera fracture zone. Asterisks indicate historically active volcanoes [after *Gutenberg and Richter*, 1954]; circles, epicenters.

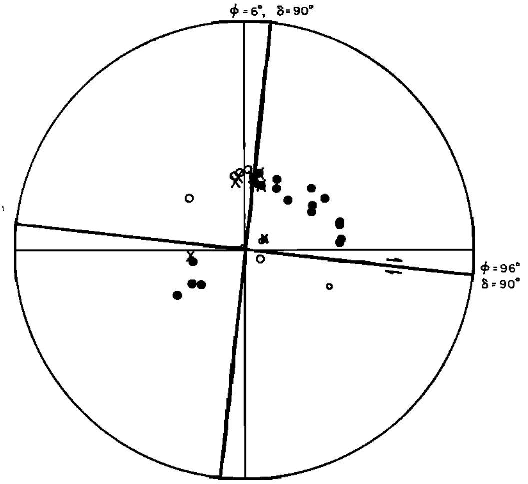

Fig. 22. Mechanism solution for earthquake on Easter fracture zone (event 15). Location and other pertinent data in Figure 3 and Table 1. Symbols same as Figure 5.

of the seismic belt [*Sykes*, 1963; *Cooke*, 1966]. The orientation of the compressional axis is nearly the same as the direction of principal horizontal stress deduced by *Lensen* [1960] for southern New Zealand. This suggests that the tectonics of this portion of the Macquarie ridge may be more similar to the tectonics of New Zealand than to the tectonics of the mid-oceanic

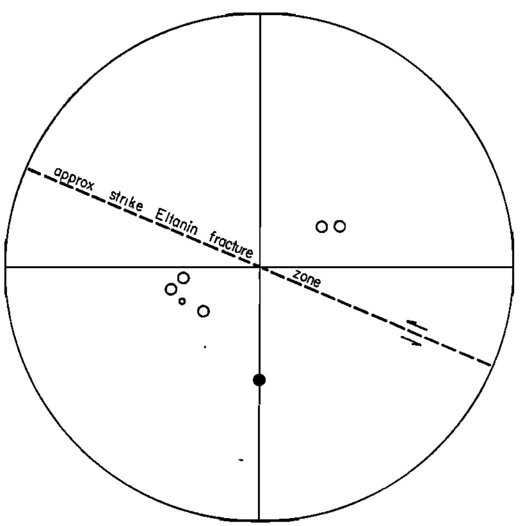

Fig. 23. Mechanism solution for event 16 on the Eltanin fracture zone in the southeast Pacific. Epicenter indicated in Figure 3. Symbols same as Figure 5.

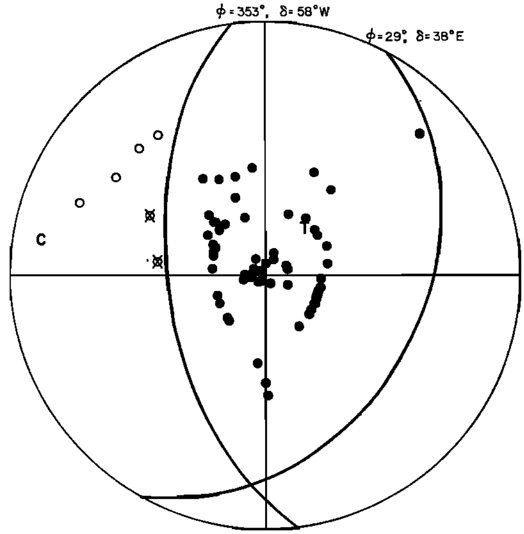

Fig. 24. Mechanism solution for event 17 on the Macquarie ridge (Figures 3 and 25). Symbols same as Figures 5 and 11.

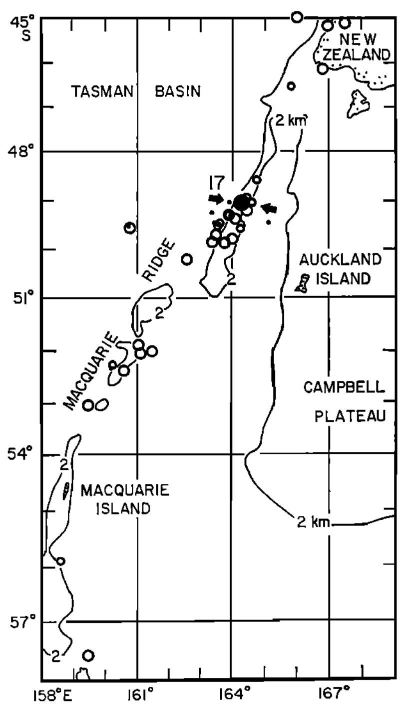

Fig. 25. Epicenters of earthquakes for period 1955–1965 on the Macquarie ridge. Inferred axis of maximum compression shown for event 17. Bathymetry after *Brodie and Dawson* [1965]. Other symbols same as Figure 4.

ridge. Because Macquarie Island is the only island in the deep oceans to be well folded, prophyllitized, and to have veins of sulphides, it seems to be partly continental in character [*Wilson,* 1963].

Comparison of Inferred Mechanisms with Those Deduced by Other Investigators

General comparison. Stauder and Bollinger [1964*a, b;* 1965] have presented solutions for seven of the earthquakes considered in this paper. *Stefánsson* [1966] has also made an extensive study of the mechanisms of two of these seven shocks. The various solutions for these earthquakes are compared in Table 2. With the exception of event 4, an earthquake preceded by a small forerunner, the strikes and dips of the remaining solutions agree within about 15°. For some of the best solutions these differences are less than 5°. The strikes and dips reported in this paper were read from an equal-area net and may be in error by 1° or 2°.

Stauder [1964] and *Hodgson and Stevens* [1964] have mentioned the general lack of agreement among the solutions presented by different workers for the same earthquake. It now seems evident that many of these disagreements arose from the poor quality of the data that were generally available before the installation of the WWSSN. Further studies with data of high quality should lead to a much better understanding of world tectonics and stress release.

Correct sense of motion. The determination of the sense of strike-slip motion on fracture zones has been one of the most important topics of this paper. Thus, it is important to inquire if the sense of motion inferred from studies of first motions could be in error by large amounts or even possibly reversed. Although geologic and geodetic evidence for displacements are not available for many earthquakes, evidence of this kind is in close agreement with the solutions inferred from first motions in the case of several prominent earthquakes. Very good agreement with geologic evidence was found in investigations of the mechanisms of the Fairview Peak earthquake of December 1954 [*Romney,* 1957], the southeast Alaska earthquake of 1958 [*Stauder,* 1960], and the Parkfield earthquake of 1966 [*McEvilly,* 1966]. *Hodgson* [1957] has cited other examples of good or fair agreement between first-motion studies and geologic and geodetic evidence. Hence, it seems highly unlikely that the inferred sense of motion on fracture zones is incorrect.

TABLE 2. Comparison of Mechanism Solutions for Earthquakes on the Mid-Ocean Ridges

		Plane Striking Easterly		Plane Striking Northerly	
Event Number	Author	Strike, deg	Dip	Strike, deg	Dip
2	Sykes	100	79°S	10	90°
	Stauder and Bollinger	101	80°S	12	86°W
3	Sykes	98	86°N	8	90°
	Stauder and Bollinger	87	78°N	−1	81°E
4	Sykes	90	86°N	0	84°E
	Stauder and Bollinger	(81)	(63°S)	(−61)	(34°N)
	Stefánsson	89	84°N	0	84°E
5	Sykes	103	90°	14	87°E
	Stauder and Bollinger	101	76°S	9	80°E
7	Sykes	106	50°N	49	57°E
	Stauder and Bollinger	91	45°N	45	55°E
9	Sykes	106	86°N	17	78°E
	Stauder and Bollinger	103	77°N	17	70°E
	Stefánsson, long-period P	107	88°N	18	79°E
	Stefánsson, short-period P	109	84°N	18	76°E
	Steffánsson, short-period S	104	81°N	12	77°E
15	Sykes	96	90°	6	90°
	Stauder and Bollinger	109	90°	20	90°

Conclusions and Discussion

Because of several remarkable improvements in seismic instrumentation and in the availability of these data, mechanism solutions of high precision can now be obtained for many areas of the world. Earthquakes on the mid-oceanic ridge and the extensions of this ridge system into East Africa and the Arctic seem to be characterized by two principal mechanisms: (1) a predominance of strike-slip motion on steeply dipping planes or (2) a large component of normal faulting with the inferred axis of tension approximately perpendicular to the ridge.

Of the ten events of the first group seven were located on the mid-Atlantic ridge and three were found on the east Pacific rise; all ten occurred on major fracture zones that intersect the crest of the ridge. In each case the inferred sense of displacement is in agreement with that predicted for transform faults; the motion is opposite to that expected for a simple offset of the ridge. Thus, displacements inferred by the use of the assumption of simple offset appear to be incorrect, and worldwide shear nets deduced by such a procedure [e.g., *Van Bemmelen*, 1964] also indicate the wrong sense of motion on oceanic fracture zones.

Seismic activity on fracture zones is confined almost exclusively to the region between the two crests of the ridge. This distribution of activity is a strong argument in favor of the hypothesis of transform faults. Information obtained from earthquake mechanisms and seismicity is, of course, limited to a time scale of a few or a few tens of years for the mid-oceanic ridge. Since a very similar behavior was found for all the fracture zones investigated in this paper, the results are very likely to approximate closely the tectonics of the ridge system for much longer periods of time.

Of the six events that are characterized by a large component of normal faulting three occurred in East Africa, one was located near the continental shelf of Siberia, and two were situated on the mid-Atlantic ridge in a region where fracture zones have not been found. Although evidence for transform faults in East Africa was not found in this study, *Bloomfield* [1966] has suggested that a transform fault may connect two portions of the Malawi rift. This zone apparently follows an old line of weakness. Although a zone of weakness might account for the development of separate segments of ridge in cases where the distance between segments is small, it is more difficult to understand how zones of weakness could alone explain the development of separate ridge crests, when this distance is hundreds of kilometers as it is in the equatorial Atlantic and in the southeast Pacific near the Eltanin fracture zone.

As *Wilson* [1965a] has pointed out, transform faults can only exist if there is crustal displacement. The deduced mechanisms and the distribution of earthquakes both seem to demand a process of sea-floor growth at or near the crest of the mid-oceanic ridge system. Transform faults also provide a relatively simple mechanism for continental drift. Although the East Africa rift valleys have been cited as examples of compressional, extensional, or strike-slip tectonics, more recent discussions have largely centered on extensional mechanisms. This interpretation became more prevalent with the realization that the mid-oceanic ridge system existed on a worldwide scale [*Ewing and Heezen*, 1956]. Unfortunately, neither the seismological evidence nor the magnetic evidence for sea-floor growth gives information directly pertinent to the tectonics of the ridges in the third dimension, depth.

Although there seems to be a considerable variation in the orientation of earthquake mechanisms in island arcs, one factor that seems to be common among many of the solutions for these regions is that the horizontal component of compression is approximately perpendicular to the strike of the arc [*Balakina et al.*, 1960; *Lensen*, 1960; *Ichikawa*, 1961; *Honda*, 1962; *Balakina*, 1962; *Ritsema*, 1964; *Isacks et al.*, 1967]. Thus, results from investigations of the mechanisms of earthquakes seem to be indicative of a system of compressional tectonics in island arcs and of extensional tectonics along the mid-oceanic ridges.

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U. S. Coast and Geodetic Survey, the Canadian seismograph network, and the institutions that have cooperated with the Lamont Observatory in the operation of long-period instruments. Dr. P. W. Pomeroy kindly made records available from new stations in Abéché, Chad, and Lamto, Ivory Coast; Dr. B. L. Isacks supplied similar records from a new network of stations in the Fiji-Tonga region of the southwest Pacific; Mr. R. J. Halliday provided microfilm copies of Canadian records. I also thank Dr. J. R. Heirtzler, W. C. Pitman, and Dr. F. J. Vine for providing preprints of recent papers and for discussions of evidence for ocean-floor spreading.

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