Marine Magnetic Anomalies, Geomagnetic Field Reversals, and Motions of the Ocean Floor and Continents[1]

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This paper summarizes the results of the three previous papers in this series, which have shown the presence of a pattern of magnetic anomalies, bilaterally symmetric about the crest of the ridge in the Pacific, Atlantic, and Indian oceans. By assuming that the pattern is caused by a sequence of normally and reversely magnetized blocks that have been produced by sea floor spreading at the axes of the ridges, it is shown that the sequences of blocks correspond to the same geomagnetic time scale. An attempt is made to determine the absolute ages of this time scale using paleomagnetic and paleontological data. The pattern of opening of the oceans is discussed and the implications on continental drift are considered. This pattern is in good agreement with continental drift, in particular with the history of the break up of Gondwanaland.

INTRODUCTION

The three previous papers of this series [*Pitman et al.*, 1968; *Dickson et al.*, 1968; *Le Pichon and Heirtzler*, 1968] have shown that a magnetic anomaly pattern, parallel to and bilaterally symmetric about the mid-oceanic ridge system, exists over extensive regions of the North Pacific, South Pacific, South Atlantic, and Indian oceans. It has been further demonstrated that the pattern is the same in each of these oceanic areas and that the pattern may be simulated in each region by the same sequence of source blocks. These blocks comprise a series of alternate strips of normally and reversely magnetized material, presumably basalt (Figure 1).

The symmetric and parallel nature of the anomaly pattern and the general configuration of the crustal model conform to that predicted by *Vine and Matthews* [1963] and may be regarded as strong support for the concept of ocean floor spreading [*Dietz*, 1961; *Hess*, 1962].

Figure 1 shows sample anomaly profiles from the various regions under discussion. Also shown are the model blocks, derived for the North Pacific profile and adjusted to fit the other oceans. The North Pacific profile is a composite using sections at different latitudes because of complex structure.

It is our purpose in this paper to derive a time scale for the sequence of magnetic polarity events predicted by the basic model and to discuss the concepts of continental drift and ocean floor spreading in terms of the anomaly pattern and the time scale.

Following *Vine and Matthews* [1963], we will assume that all the linear magnetic anomalies, sub-parallel to the ridge axis, are due to geomagnetic field reversals. If that theory is basically in error, the conclusions in this paper do not apply. Yet, if that theory is applied carefully, many geophysical and geological observations, previously thought to be unrelated or casually related, are seen to have a simple unified explanation.

CHOICE OF TIME SCALE

The most obvious method for deriving a detailed time scale for the magnetic anomaly is by extrapolation from well-dated paleomagnetic events. *Pitman and Heirtzler* [1966], *Vine* [1966], *Pitman et al.* [1968], *Dickson et al.* [1968], and *Le Pichon and Heirtzler* [1968] have demonstrated that, for the various sections of mid-oceanic ridge under discussion, the mag-

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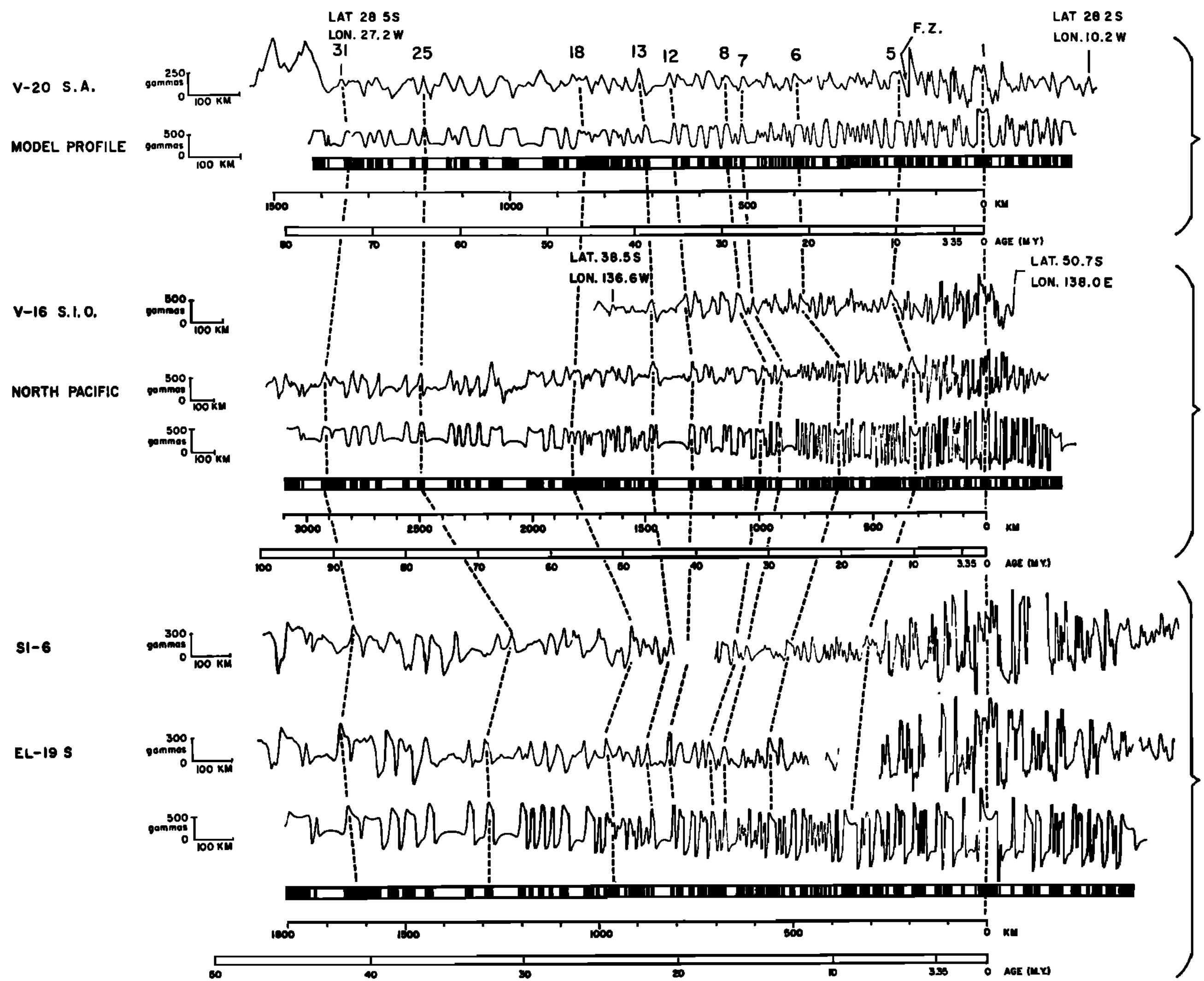

Fig. 1. Sample magnetic profiles from various oceans. The South Atlantic (S.A.) profile is from the paper by *Dickson et al.* [1968], the South Indian Ocean (S.I.O.) profile is from *Le Pichon and Heirtzler* [1968], and the remaining profiles (North Pacific, SI-6, EL-19S) are from *Pitman et al.* [1968]. Beneath each of the observed profiles is a theoretical profile calculated from the normally magnetized (black) and reversely magnetized (white) bodies shown. Each body is 2 km thick. With each model is a time scale constructed by assuming an age of 3.35 m.y. for the end of the

netic anomaly pattern associated with the axial zone may always be related to the known sequence of magnetic polarity events of the past 3.35 m.y. by assuming a constant spreading rate. The fault plane solutions of *Sykes* [1967] show that the movement between offset ridge axes is in agreement with that predicted by *Wilson* [1965] for a transform fault, thus indicating that the spreading process is active in these regions today.

In Figure 1 are displayed observed magnetic profiles from the North and South Pacific, the South Indian, and the South Atlantic oceans and model bodies that could account for the observations. The latitude and longitude of the end points of each profile are noted on the figure. Study of the theoretical profiles for the three models shows that these models can account for the observed profiles immediately above them. With each model an age scale is given. Each scale is based on the date of 3.35 m.y. for the beginning of the Gauss normal polarity epoch [*Doell et al.*, 1966]. The time scales obviously differ and are not linearly related, since the models for the South Pacific and the South Atlantic were derived from the basic model for the North Pacific by adjusting the set of model blocks according to the curve for the relative spreading rate. The relative spreading rate curves (Figure 8, *Pitman et al.* [1968] and Figure 2 of this paper) though nonlinear, are continuous. The problem is to choose the most reasonable time scale.

T. Saito (personal communication) has paleontologically determined the age at the bottom of a core (V 20–80) taken at 46°30′N, 135°W as Lower to Middle Miocene (13–26 m.y.). The core location is on anomaly 6. By the North Pacific and South Atlantic standards the magnetic basement at anomaly 6 should be 20–22 m.y. old. The South Pacific time scale suggests an age of 14 m.y. for this basement, much younger than the age of the core.

The core was taken on an outcrop where no sediment was detected by seismic reflection methods. The seismic reflection technique employed, however, was unable to resolve reflectors less than 50 meters in thickness. Thus, allowing for some sediment beneath the core, we can accept the older date for anomaly 6 as more reasonable.

Ewing et al. [1968] have found the eastern boundary of layer A′ (as detected by reflection techniques) in the North Pacific to be just west of anomaly 32. They have proposed an Upper Cretaceous age (70 m.y.) for this layer. The South Pacific time scale would suggest an age of 47 m.y. for anomaly 32. Unless there has been a major discontinuity in spreading rates, the South Pacific time scale is in error at this point by a factor of 2.

A Cretaceous core [*Le Pichon et al.*, 1966]

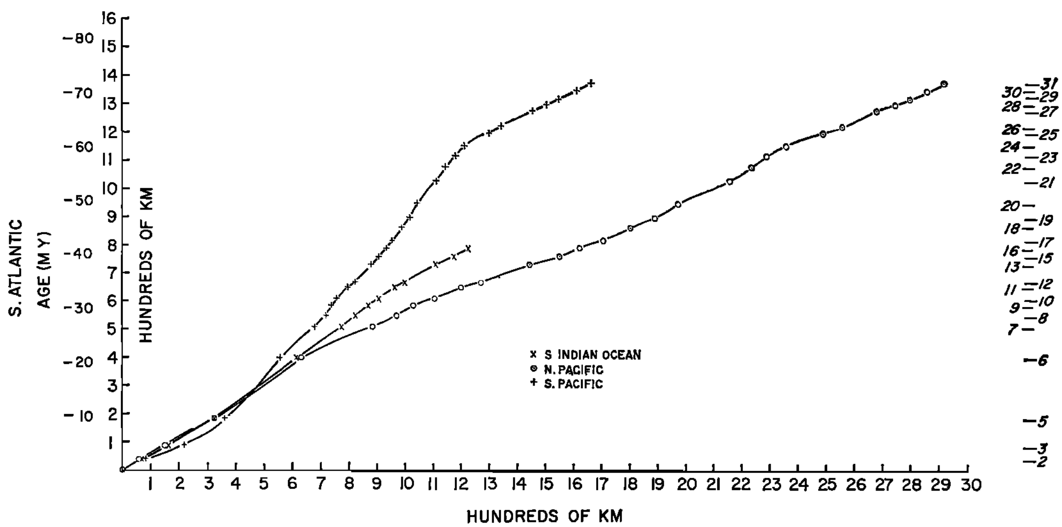

Fig. 2. The distance to a given anomaly in the South Atlantic (V-20 S.A.) versus distance to the same anomaly in the South Indian, North Pacific, and South Pacific oceans. Numbers on right refer to anomaly numbers.

taken at the base of the Rio Grande rise in the South Atlantic just west of anomaly 31 supports the South Atlantic or the North Pacific time scale.

As stated previously, the curves shown plotted in Figure 8 of *Pitman et al.* [1968] and in Figure 2 of this paper may be regarded as indicative of the relative spreading rates between several major sections of the mid-oceanic ridge system. In Figure 8 of *Pitman et al.* [1968] the North Pacific has been used as a standard and in Figure 2 of this paper the South Atlantic (V-20 SA) has been used. In both cases the South Pacific (EL-19S) follows the same general curvature, the points of inflection occurring in the vicinity of anomalies 5 and 24. The spreading rates for both the North Pacific and the South Atlantic relative to the spreading rate for the South Pacific may have varied in the same way with respect to time, the spreading rates in both the North Pacific and the South Atlantic may have remained relatively constant and the South Pacific spreading rate may have varied with time, or both processes may have occurred simultaneously. To us it seems most likely that the South Pacific spreading rate has varied with time. For these reasons the South Pacific can be eliminated as a standard.

The Indian Ocean (V-16 SIO) has been eliminated because the anomalies extend only to number 16, at which point the profile ends at the base of the south Australian continental slope.

It has been demonstrated [*Pitman and Heirtzler,* 1966] that the ELT-19 N axial model may be applied to the Reykjanes ridge if a constant spreading rate of 1 cm/yr is assumed for this region. *Dickson et al.* [1968] have applied this model to two regions of the mid-Atlantic ridge in the South Atlantic, again assuming a constant spreading rate. One case, V-20 S.A., is shown here (Figure 1). The other, *V*-18 (latitude 30.5°S, longitude 13.7°W), is shown in Figure 7 of *Dickson et al.* [1968]. In both cases, the fit between the measured and the computed profiles is good. The applicability of this model to the North Atlantic (Reykjanes ridge) and the South Atlantic (mid-Atlantic ridge) indicates that the spreading rate in each of these regions has been constant for the past 10 m.y.

Vine [1966], in comparing the details of the axial zone pattern of ELT-19 N and Juan de Fuca ridge, suggested that the spreading rate at the Juan de Fuca ridge has not been constant over the past 10 m.y. but has decreased from 4.4 to 2.9 cm/yr.

The time scale extrapolated from the V-20 S.A. profile has been selected as a standard because:

1. The relative spreading in the South Pacific appears to have varied considerably with time and the paleontological evidence suggests that the South Pacific time scale is too young by a factor of 2.
2. The North Pacific profile is distorted at the ridge axis.
3. The anomaly pattern for the South Indian Ocean is not sufficiently long.

The bottom of Figure 1*A* shows the extrapolated time scale based on the 3.35-m.y. date for the end of the Gilbert reversed epoch. The date of 80 m.y. just beyond anomaly 32 is close to the 73-m.y. date given by *Vine* [1966] for the same point.

The possible error inherent in such an extrapolation cannot be over emphasized. By adopting the South Atlantic time scale we are assuming that the ocean floor has been spreading at a constant rate in the locality of the V-20 profile for the last 80 m.y.

Dividing the distance to the South Atlantic model magnetized bodies by the calculated axial zone spreading rate of 1.9 cm/yr [see *Dickson et al.,* 1968] gives the times of the magnetic reversals and the corresponding ages for the normal and reversed magnetic intervals. The ages of the normally polarized intervals are given in Table 1. The intervening times are reversely polarized.

In Figure 3 anomaly numbers are shown with their corresponding geologic and absolute ages. If the ages of these anomalies are placed on a map for the areas where anomalies had previously been identified only by number, the age map of Figure 4 results.

There are three principal observations that conflict with the proposed time scale. The first of these is the age of 27 m.y. determined by the potassium-argon method for a basalt boulder from Cobb seamount on the East Pacific rise [*Budinger and Enbysk,* 1967]. According to the

TABLE 1. Intervals of Normal Polarity (m.y.)

0.00– 0.69	18.91–19.26	40.03–40.25
0.89– 1.93	19.62–19.96	40.71–40.97
1.78– 1.93	20.19–21.31	41.15–41.46
2.48– 2.93	21.65–21.91	41.52–41.96
3.06– 3.37	22.17–22.64	42.28–43.26
4.04– 4.22	22.90–23.08	43.34–43.56
4.35– 4.53	23.29–23.40	43.64–44.01
4.66– 4.77	23.63–24.07	44.21–44.69
4.81– 5.01	24.41–24.59	44.77–45.24
5.61– 5.88	24.82–24.97	45.32–45.79
5.96– 6.24	25.25–25.43	46.76–47.26
6.57– 6.70	26.86–26.98	47.91–49.58
6.91– 7.00	27.05–27.37	52.41–54.16
7.07– 7.46	27.83–28.03	55.92–56.66
7.51– 7.55	28.35–28.44	58.04–58.94
7.91– 8.28	28.52–29.33	59.43–59.69
8.37– 8.51	29.78–30.42	60.01–60.53
8.79– 9.94	30.48–30.93	62.75–63.28
10.77–11.14	31.50–31.84	64.14–64.62
11.72–11.85	31.90–32.17	66.65–67.10
11.93–12.43	33.16–33.55	67.77–68.51
12.72–13.09	33.61–34.07	68.84–69.44
13.29–13.71	34.52–35.00	69.93–71.12
13.96–14.28	37.61–37.82	71.22–72.11
14.51–14.82	37.89–38.26	74.17–74.30
14.98–15.45	38.68–38.77	74.64–76.33
15.71–16.00	38.83–38.92	
16.03–16.41	39.03–39.11	
17.33–17.80	39.42–39.47	
17.83–18.02	39.77–40.00	

magnetic anomaly pattern, the seamount should be no older than 3.5 m.y. [*Vine*, 1966]. The boulder may not have developed as part of the seamount but may be a glacial erratic. Further, *Dymond et al.* [1968] have dated two basalt samples drilled from the top of Cobb seamount as less than 2 m.y. *Ewing et al.* [1966] and *Saito et al.* [1966] have pointed out that a Lower Miocene boulder was dredged at the intersection of the Atlantis fracture zone and the rift valley of the mid-Atlantic ridge. Although the magnetic anomalies near the Atlantis fracture zone in the North Atlantic have not been studied, one would assume that spreading has occurred there just as it has immediately to

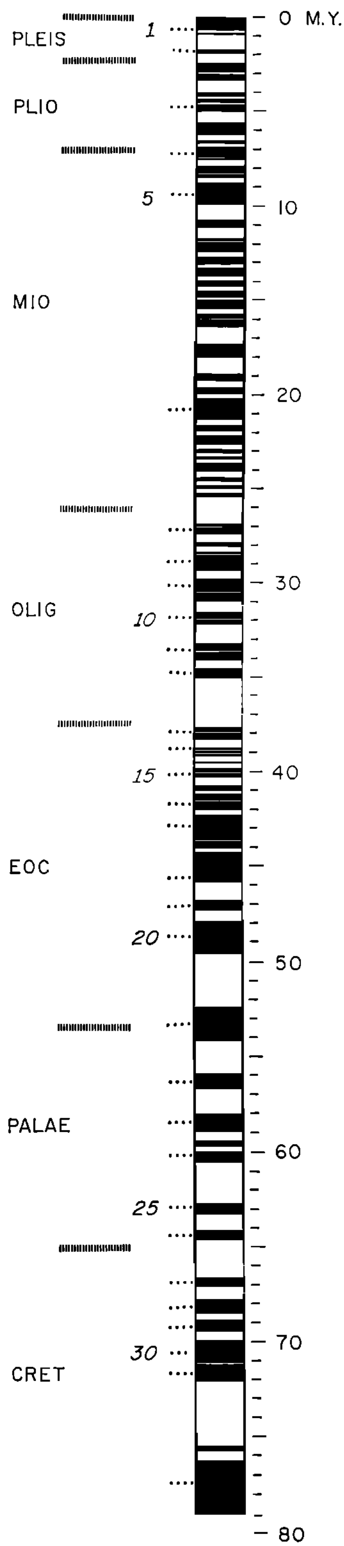

Fig. 3. The geomagnetic time scale. From left to right: Phanerozoic time scale for geologic eras, numbers assigned to bodies and magnetic anomalies, geomagnetic field polarity with normal polarity periods colored black.

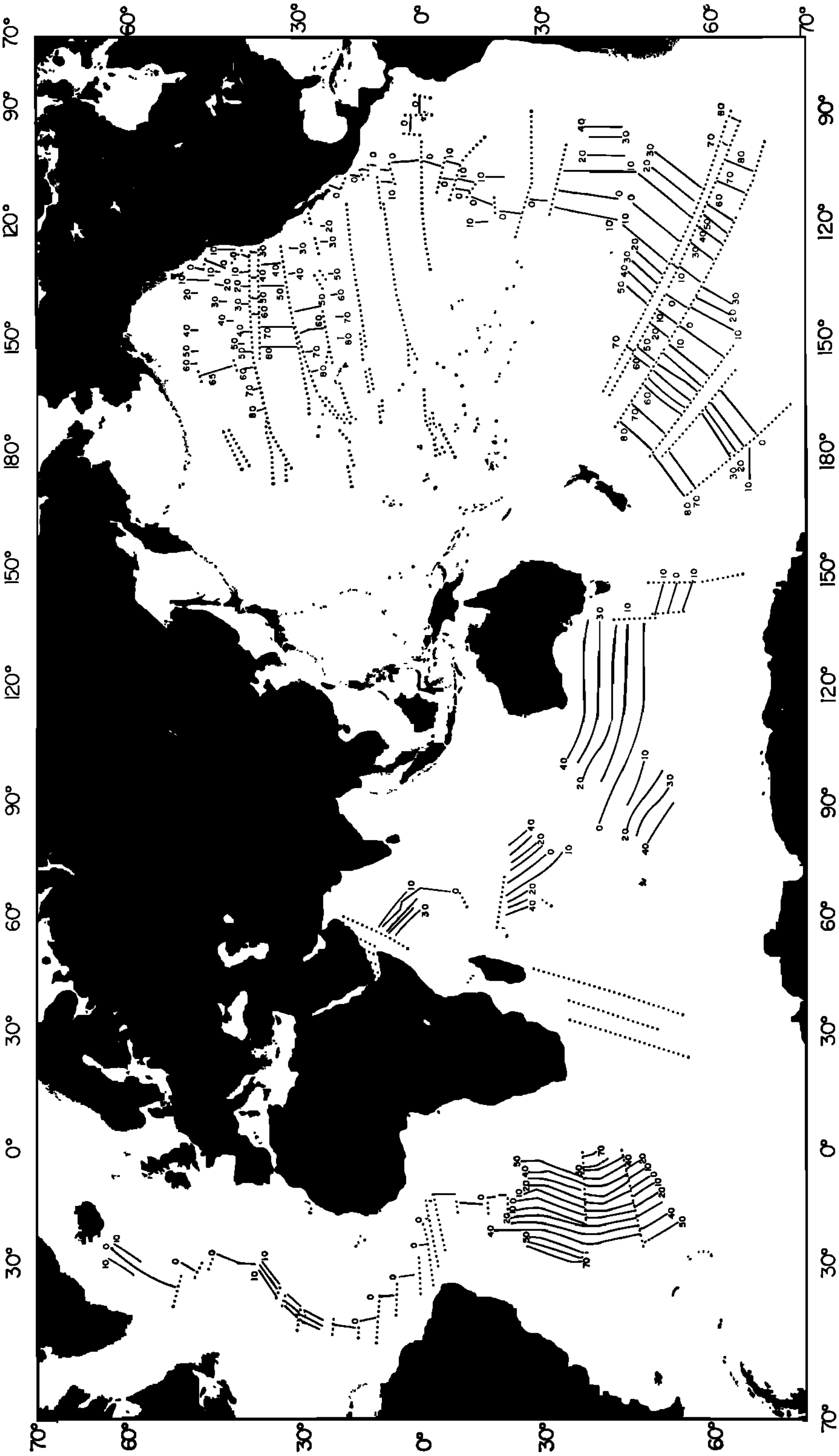

Fig. 4. Isochron map of the ocean floor according to the magnetic anomaly pattern. Numbers on isochron lines represent age in millions of years. Dotted lines represent fracture zones.

the south [*Phillips*, 1967; *Van Andel et al.*, 1967]. L. R. Sykes (personal communication) has pointed out that although the boulder was located within 10 km of the axis on the north side of the fracture zone, it is about 60 km from the axis on the south side. Hence, it is impossible to predict the age of such a boulder if we assume the existence of sea floor spreading.

Recently, *Ewing and Ewing* [1967] have documented the existence of a significant increase in sediment thickness occurring near anomaly 5, approximately 10 m.y. ago, and have interpreted this as probably marking an interruption in spreading. Our data cannot exclude the possibility of such an interruption, provided that it occurred simultaneously everywhere. Thus, this fact introduced a further restriction in the interpretation of our time scale.

Characteristics of Sequence of Geomagnetic Field Reversals

Although it is important to substantiate this history of geomagnetic reversals by other, independent means, it will be difficult to do so in any detailed fashion. The numerous and relatively rapid reversals make it difficult to distinguish any particular magnetic event from its neighbors. Even if samples of the magnetic basement can be recovered by deep drilling operations, age determinations by the present techniques probably cannot be made with sufficient precision.

For example, a dating technique that can ascertain age to within 10% could identify several events that are less than 10 m.y. old, but this technique would have insufficient accuracy to identify a particular event older than 10 m.y. If the dating technique could identify an event whose length is only 5% of its age, we might be able to identify an event as old as the long reversed period at 49.6 to 52.4 m.y. but nothing older. With drilling, too, one can never be sure of sampling the magnetic basement instead of a local magnetic inhomogeneity.

Figure 3 shows the geomagnetic time scale with geologic ages according to the Phanerozoic time scale [*Anonymous*, 1964]. Among the 171 reversals there are many short events throughout the geomagnetic time scale, some as short as 30,000 years. As shown in Figure 5, however, in which the frequency of reversals has been plotted as a function of time, the older events are generally longer. The graphs were constructed by determining the average number of reversals that occurred during periods of 2, 5, and 10 m.y., respectively. The frequency of reversals was appreciably lower prior to 40 m.y. ago.

The distribution of the lengths of normal and reversed intervals is illustrated by the histograms of Figure 6. The average normal in-

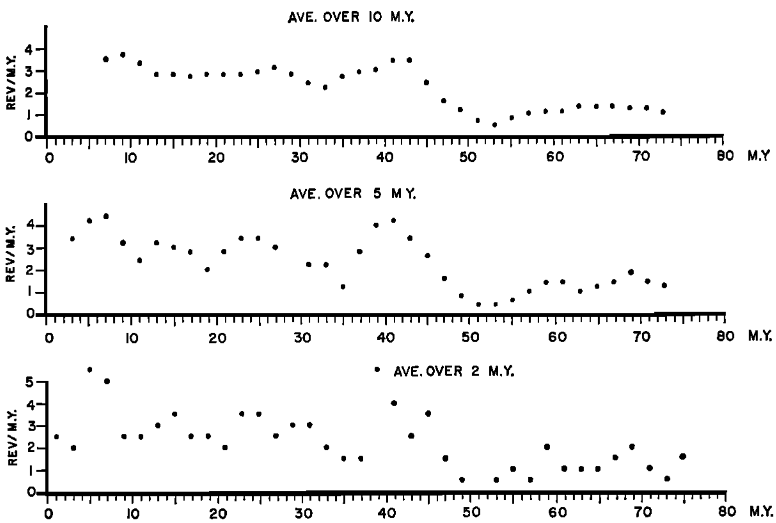

Fig. 5. Frequency of geomagnetic field reversals as a function of time averaged over intervals of 2, 5, and 10 m.y.

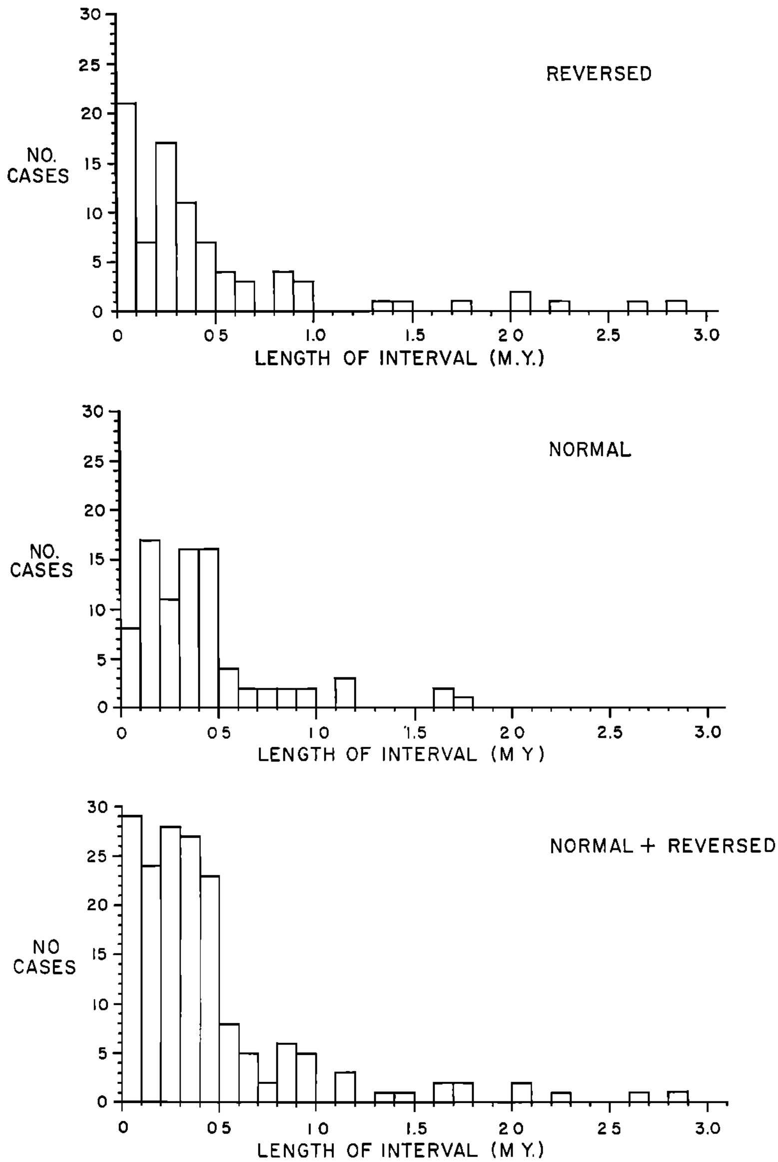

Fig. 6. Distributions of the lengths of magnetic states for normal polarity and reversed polarity and for the length of intervals regardless of polarity.

terval is 0.42 m.y. and the average reversed interval is 0.48 m.y. These nearly identical average lengths and the similar shapes of the normal and reversed distributions suggest that there is no fundamental difference in the stability of the normal and reversed magnetic states. Only 15% of the normal intervals were longer than the present normal 700,000-year interval, although some existed for nearly 3 m.y.

The completeness with which the time scale accounts for details in the marine anomaly profile near the axis is illustrated in Figure 7. Ten observed profiles are compared with the theoretical profile for the axial region of the South Pacific and Indian oceans, where the spreading is relatively fast and small anomalies are well displayed. Anomalies that occur with some consistency are labeled 'X' and 'Y.' These anomalies would presumably be respectively

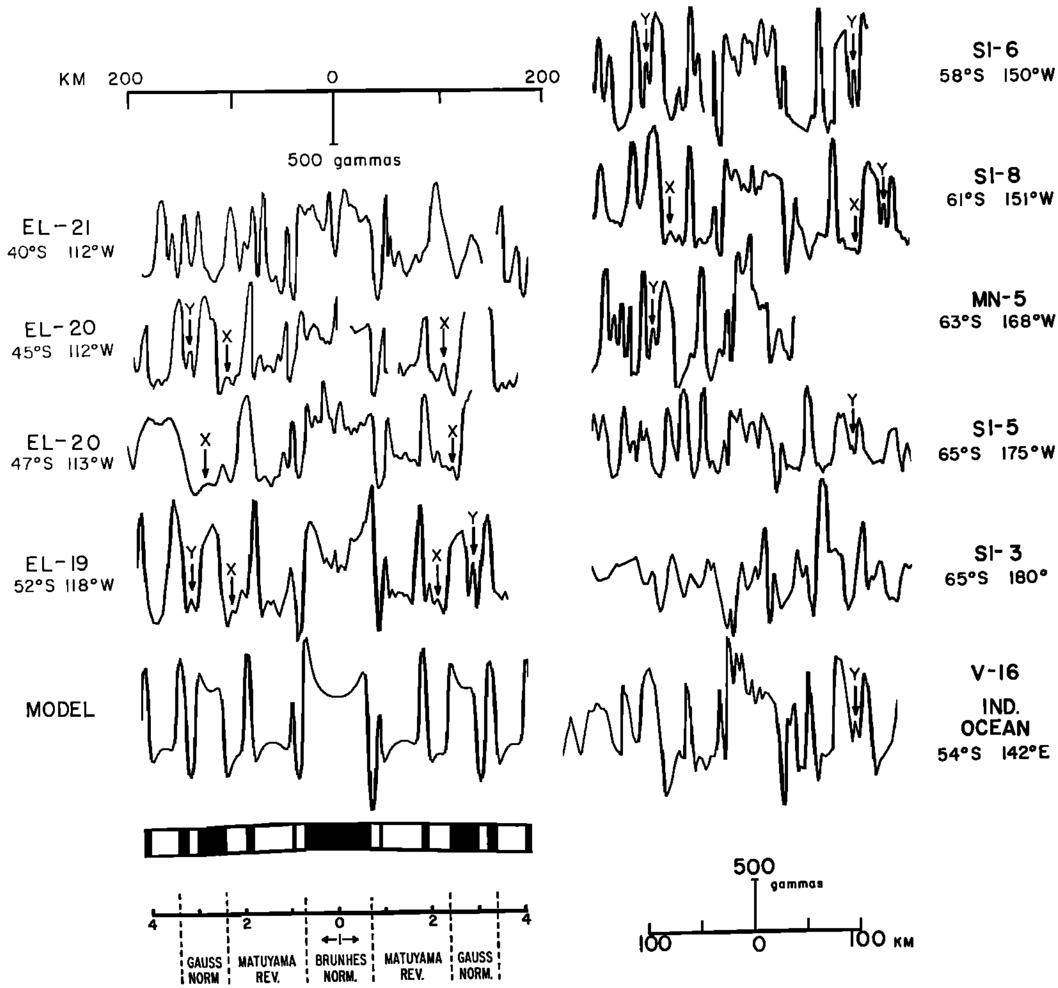

Fig. 7. Ten observed axial magnetic profiles with theoretical profile for known reversals during the last 4 m.y. Anomalies X and Y are not accounted for with the model.

due to splits in the Olduvai and Monmouth events within the Matuyama and Gauss epochs. Since they are identified with more difficulty and less consistency than other anomalies, we hesitate to interpret them as due to magnetic polarity events. *McDougall and Chamalaun* [1966] and *Vine* [1966] have postulated a normal magnetic polarity event corresponding to Y named by McDougall and Chamalaun the 'Kaena' event. N. D. Opdyke (personal communication) has found evidence for the Kaena from paleomagnetic studies of deep-sea cores. *McDougall and Wensink* [1966] have proposed a Gilsa event, a period of normal magnetic polarity, between the Jaramillo and Olduvai. We find no consistent evidence for such an event in the magnetic profiles studied. To date no paleomagnetic evidence has been presented for an event of positive polarity corresponding to the anomaly X.

Comparison of the geomagnetic time scales presented here and the time scale as determined by *Hays and Opdyke* [1967] from the direction of magnetization of ocean cores emphasizes that the magnetic anomalies are due to magnetic reversals. Figure 8 illustrates the magnetic stratigraphy of three Pacific-Antarctic cores. It also shows the history of the magnetic reversals that *Pitman and Heirtzler* [1966] found from marine anomalies and the polarity history ac-

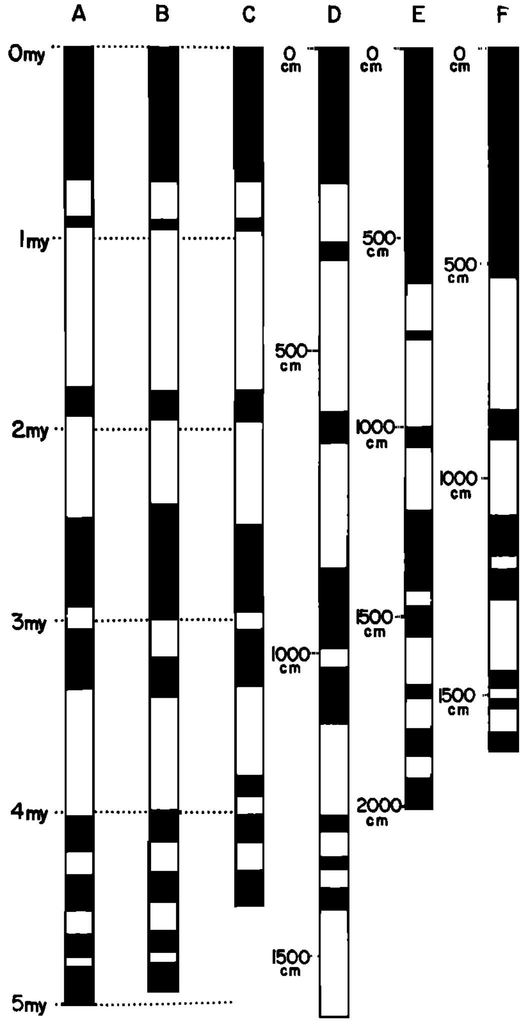

Fig. 8. Geomagnetic field reversals for the last 5 m.y. from ocean sediment cores compared with field reversals according to the magnetic anomaly pattern. Column A represents the geomagnetic time scale according to this paper; column B, according to *Pitman and Heirtzler* [1966]; column C, according to sediment cores [*Hays and Opdyke,* 1967]. Columns D, E, and F show the magnetic states of the three cores used by Hays and Opdyke.

cording to this paper. The scale used by *Pitman and Heirtzler* [1966] for these axial and near-axial anomalies differs slightly from the scale reported here in the first part of Table 1 because more profiles have since been examined.

Dalrymple et al. [1967] have studied Pliocene geomagnetic epochs from forty-five rock samples of the western United States. The polarities and ages that they found are illustrated in Figure 9 along with the geomagnetic time scale of this paper. When the probable error of the age determinations, shown by the bar, is considered, the correspondence is generally good. Contradictions in the two scales are evident with the specimens W 10, W 23, and W 24. These discrepancies might be explained by the existence of magnetic polarity events of very short duration. It is also possible that the spreading has been discontinuous [*Ewing and Ewing,* 1967]. As pointed out previously, however, this section of the model (from 10 m.y.

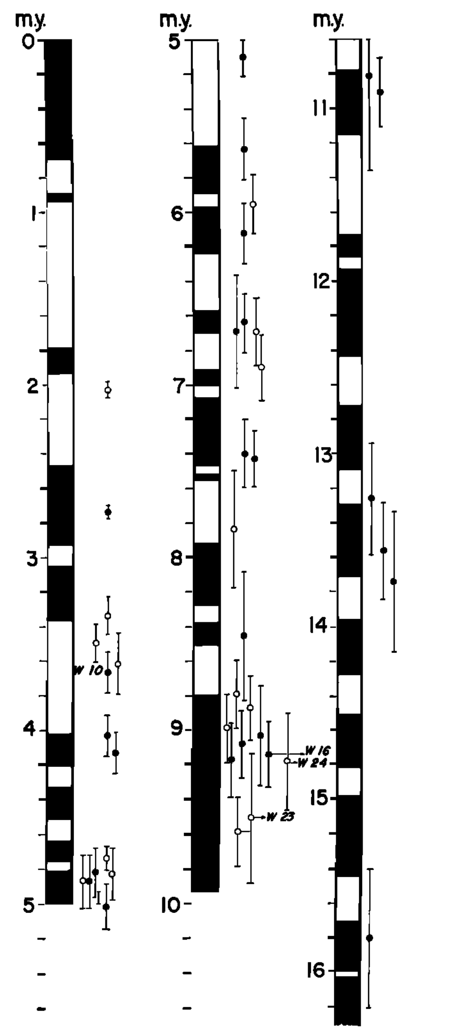

Fig. 9. Geomagnetic field polarity of Pliocene rock specimens [*Dalrymple et al.,* 1967] compared with field polarity according to the magnetic anomaly pattern.

B. P. to the present) has been shown to be applicable to the South Pacific and Reykjanes ridge [*Pitman and Heirtzler,* 1966], to the Juan de Fuca ridge [*Vine,* 1966], and to the South Atlantic [*Dickson et al.,* 1968], suggesting that the spreading has been continuous and at a constant rate in each region or that, if discontinuities have occurred, they have been simultaneous in all these regions.

Coupling between Moving Ocean Floor and Continental Masses: Relation of Sea Floor Spreading to Continental Drift

It is most important to determine if coupling is present between the moving ocean floor and the continental blocks. If such coupling exists, the magnetic pattern in the ocean floor can be used to reconstruct the detailed motion of the continents. Not only would the magnetic pattern give the detailed paths followed by the continents but also the extent of marine magnetic data available today would permit a study of the synoptic motions of continents.

It was assumed by *Hess* [1962] and *Dietz* [1961] that sea floor spreading was responsible for the drift of some of the continents. They assumed that the moving ocean floor in all oceans, except the Pacific, rafted the bordering continents ahead of it. In the Pacific, however, the moving floor did not push the continents; on the contrary, the continents encroached upon the ocean floor. The circum-Pacific trenches were interpreted as the places where the moving ocean floor turned down under the advancing blocks of crust. Although this study does not answer the question of why most circum-Pacific continental masses are encroaching on the Pacific instead of drifting away from it, the distribution of relative ocean floor spreading rates suggests that the oceanic crust that is rafting or pushing a continental block has the slower spreading rate.

If the southern continents have been drifting away from a fixed Antarctica while maintaining a median ridge, the ridge must also have been drifting [*Wilson,* 1965] and the apparent ocean floor spreading rates are only relative to the moving axis of this ridge. Various data support the thesis that the New Zealand plateau was once against Antarctica: the direction and length of fracture zones east of New Zealand, the continental nature of the plateau [*Brodie,* 1964], the match of the 80-m.y. isochron lines (Figure 4) against the plateau, and the correlation of structural units and petrographic provinces [*Wright,* 1966].

If only the continents have moved, the amount of offset along any fracture zone should be constant. Study of Figure 4 shows, however, that the offset along the fracture zones at the base of the New Zealand plateau gradually increases to the southeast. If ocean floor spreading does not involve large-scale distortion of the oceanic crust [*Morgan,* 1968] and if the direction of motion of the continents is parallel to the fracture zones, the increase in offset of the anomalies to the southeast from the New Zealand plateau suggests that the Pacific-Antarctic ridge has migrated to the southeast away from New Zealand.

It is also possible that the variation in offset results from different spreading rates across the fracture zones. If the rate of sea floor spreading in an area between two fracture zones has varied independently of that in adjacent areas, the observed isochron displacement pattern shown in Figure 4 could result without eastward migration of the ridge axis. Such a pattern of spreading would result, however, in seismically active fracture zones along their whole length and in distortion of the adjacent continents. There is no evidence that this is so.

Pattern of Recent Ocean Floor and Continental Motion

The pattern of recent motion in the oceans is summarized in Figure 10 and Table 2. Considered on a worldwide scale, one can recognize four active lines of spreading in the Atlantic Ocean, the Arctic Ocean, the Indian Ocean, and the Pacific Ocean. With the exception of the Arctic Ocean, both spreading rates parallel to the fracture zones for the last 10 m.y. and the strikes of fracture zones have now been determined along their whole length. Although in many places the knowledge of the pattern of spreading is still rather poor, no major gap in geographic coverage exists. It is now possible to test critically the spreading floor hypothesis by examining whether the geometry of this pattern of spreading is compatible with the observation that, in general, no major large-scale distortions of continental blocks or of

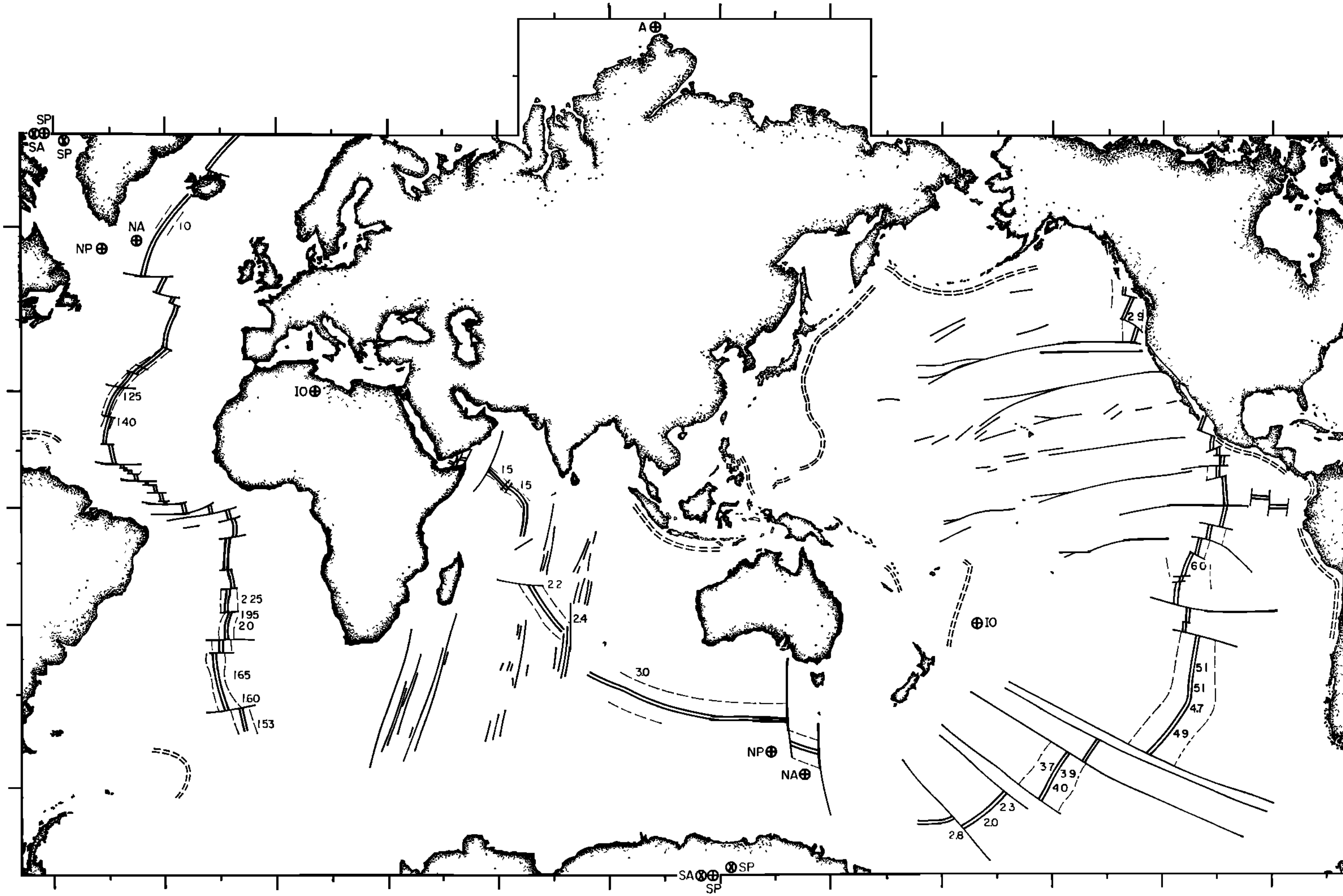

Fig. 10. Location of mid-ocean ridge axis, fracture zones, and trenches. The double line defines the axis; the adjacent dashed lines define the 10-m.y. isochron. Numbers near the axis give the half spreading rate in centimeters per year. Small circles indicate poles of spreading for the North Atlantic (N.A.), South Atlantic (S.A.), North Pacific (N.P.), South Pacific (S.P.), Arctic (A), and Indian Ocean (I.O.). A plus within these circles indicates poles according to fracture zones; a cross within the circles, poles according to spreading rates.

TABLE 2. Spreading Rates

Pacific Ocean			Atlantic Ocean			Indian Ocean		
Lat.	Long.	Rate	Lat.	Long.	Rate	Lat.	Long.	Rate
48°N	127°W	2.9	28°N	44°W	1.25	19°N	40°W	1.0
17°S	113°W	6.0	22°N	45°W	1.4	13°N	50°W	1.0
40°S	112°W	5.1	25°S	13°W	2.25	7°N	60°W	1.5
45°S	112°W	5.1	28°S	13°W	1.95	5°N	62°W	1.5
48°S	113°W	4.7	30°S	14°W	2.0	22°S	69°W	2.2
51°S	117°W	4.9	38°S	17°W	2.0	30°S	76°W	2.4
58°S	149°W	3.9	41°S	18°W	1.65			
58°S	149°W	3.7	47°S	14°W	1.60			
60°S	150°W	4.0	50°S	8°W	1.53			
63°S	167°W	2.3						
65°S	170°W	2.0						
65°S	174°W	2.8						

oceanic blocks are currently observed. For example, if the Atlantic Ocean is opening at the mid-Atlantic ridge, the movement should occur in such a way that it does not deform or distort the large bodies of horizontally stratified sediments lying in its basins and on the continental margins. Advocates of continental drift have long recognized that the continents should be displaced as rigid crustal blocks. Recent studies of the physiography of the ocean floor and the distribution of sediment have demonstrated that most oceanic crustal blocks do not show evidence of major compression or distortion. Thus, as pointed out by *Morgan* [1968], the motion can be described as the rotation of rigid blocks on the spherical surface of the earth, with the only modification of these blocks occurring at the crests of the ridges, along the trenches, and within regions of major compressive folding. Within a rigid block, motion everywhere should parallel the fracture zones, which should form small circles centered on the pole of rotation of this movement. Also, the angular velocity of rotation about some pole should be the same everywhere in the absence of relative movement along fracture zones outside the region between the offset ridge axes. In the region between the offset ridge axes, the motion is that of a transform fault [*Wilson*, 1965]. This implies that the spreading velocity increases as the sine of the distance from the pole of rotation and reaches a maximum at the equator of rotation. *Morgan* [1968] has shown that the fracture zones in the Atlantic Ocean between 30°N and 10°S approximate small circles centered at a pole near the southern tip of Greenland and that the previously determined spreading velocities roughly agree with the velocities predicted by opening of the Atlantic Ocean about this pole. Similarly, Morgan showed that the sets of faults along the west coast of North America (e.g., the San Andreas and Denali fault systems) are centered about a pole of rotation situated near the southern tip of Greenland.

The more evenly distributed information now available on the spreading rates and strikes of fracture zones along three of the four active lines of spreading enable us to carry this analysis further. For the Atlantic, Indian, and Pacific oceans one can determine whether one pole of rotation can account for the variation of spreading rates and strikes of fracture zones along the active line of spreading.

Using least squares, we have independently obtained the pole best fitting the spreading rates and the pole best fitting the strikes of the fracture zones [see *Le Pichon*, 1968, for details]. Ideally, these two poles should coincide. Table 3 lists the positions of the poles of rotation so obtained and Figure 10 shows their location. In general, the distribution of spreading rates and fracture zones within each ocean agrees well with a simple rotation about a pole. The disagreement is largest in the Indian Ocean, where the fracture zones east of the Owen fracture zone do not obey a simple pattern and where the spreading rates continue to increase along the southern part of the ridge south of Australia at a distance greater than 90° from

TABLE 3. Poles of Rotation

	Method of Determination*	Position		Number of Observations	Standard Deviation, deg
		North	South		
North Pacific	F.Z.	53°N, 47°W	53°S, 133°E	32	5.7
South Pacific	F.Z.	70°N, 62°W	70°S, 118°E	6	4.5
South Pacific	S.R.	69°N, 57°W	69°S, 123°E	11	0.06
North Atlantic	F.Z.†	58°N, 37°W	58°S, 143°E	18	2.9
South Atlantic	S.R.	70°N, 65°W	70°S, 115°E	9	0.07
Indian Ocean	F.Z.	26°N, 21°E	26°S, 159°W	5	5.1
Arctic Ocean	F.Z.	78°N, 102°E	78°S, 78°W	5	10.

* S. R. indicates spreading rate; F.Z., fracture zone.
† From *Morgan* [1968].

the pole of rotation at 30°N, 10°E. By contrast, in the South Pacific the whole pattern is simply explained by a single rotation. Similarly, in the equatorial and northern Atlantic Ocean the strike of the fracture zones is satisfied by a single north pole of rotation located near Greenland. Although the distribution of spreading rates in the South Atlantic agrees essentially with this rotation, it implies a north pole situated about 10° farther north. Similarly, the south pole for the South Pacific seems to lie about 10°S of the south pole for the North Pacific (see Figure 10). Within the accuracy of the determination the poles for the North Pacific and the equatorial and northern Atlantic (south of 30°N) coincide, and the poles for the South Pacific and South Atlantic coincide. All poles for both Atlantic and Pacific oceans lie within a circle centered in the Labrador Sea having a radius less than 10°. This result indicates that the two major movements of spreading in the Atlantic and Pacific oceans open about the same axis of rotation. Consequently, the general picture emerging from this analysis is one of great simplicity with the Atlantic and Pacific oceans opening about the same axis, which is slightly inclined to the rotational axis of the earth, and the Indian Ocean opening about an axis between the Pacific and Atlantic oceans.

Figure 11 illustrates this opening by using a Mercator projection centered on the axis passing through the South Pacific pole of rotation (69°N, 57°W). On a Mercator projection, latitudes are horizontal lines, longitudes are vertical lines, and the scale is everywhere proportional to the inverse of the sine of the distance from the pole. Thus, if the projection is centered on the pole of rotation, fracture zones should coincide with latitudes, ridge crests should coincide with longitudes, and the distance between the ridge crest and a nearby magnetic anomaly (on the map, anomaly 5, about 10 m.y. ago) should be everywhere constant. Figures 10 and 11 should be compared to see how all these requirements are met. Because the pole of rotation chosen was the one for the South Pacific, the agreement is best in the South Pacific. The present ridge crest and associated set of fracture zones (e.g., the San Andreas fault system) in the equatorial and northern Pacific Ocean also fit this pole of rotation well. The Juan de Fuca and Gorda ridges agree particularly well, and the San Andreas also essentially agrees with this pattern of movement. By contrast, the set of fracture zones in the northern and equatorial Pacific (e.g., the Mendocino and Clipperton fracture zones), which, according to *Morgan* [1968], fits a pole near 79°N, 111°E, completely disagree with the present pattern of movement (see Figure 11). Because the position of anomaly 5 in the northern and equatorial Pacific agrees with the old pattern of movement shown by these fracture zones, the present pattern must have established itself since 10 m.y. ago. Prior to 10 m.y. the South Pacific was moving about the same pole as now, but the North Pacific was moving about a different pole. Perhaps as a result of the shift in the North Pacific pole in the Pliocene the area near the Galapagos Islands has been subjected to extension, and the observed

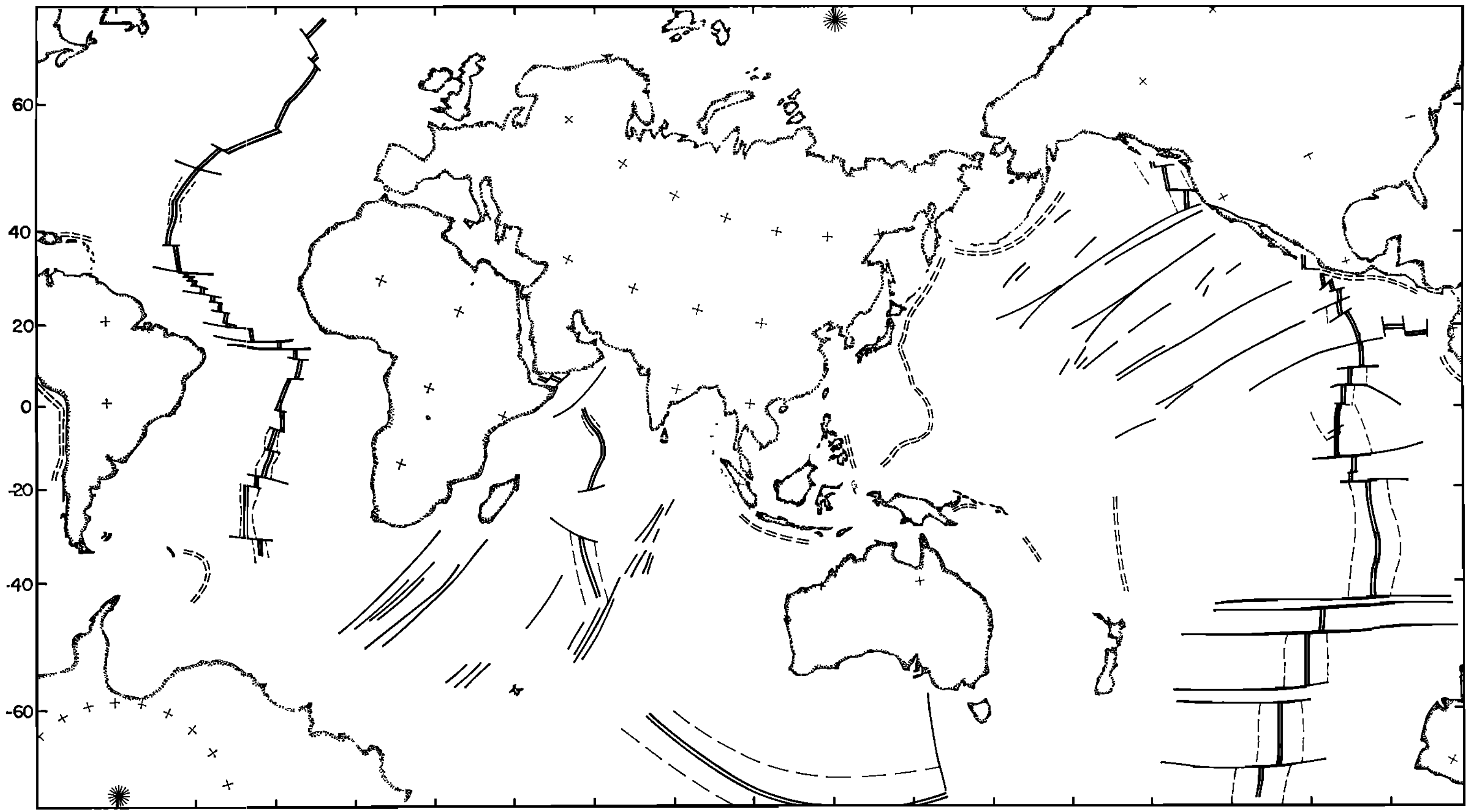

Fig. 11. Locations of mid-ocean ridge axis, fracture zones, and trenches. The poles of this mercator projection are the South Pacific poles of rotation (north pole located at 69°N, 57°W). The stars show the present location of the geographic poles, and the plus signs indicate the intersections of present latitudes and longitudes at 20° intervals. Note how, on this projection, the fracture zones in the South Pacific are along latitude lines, the ridge crest is along longitude lines, and the distance to anomaly 5 does not change with distance from the pole of rotation. This confirms that the movement of opening of the South Pacific Ocean corresponds to a rotation around a point situated near 69°N, 57°W.

symmetric magnetic pattern records crustal material upwelling along an east–west line on the east side of the ridge axis for at least 5 m.y. [*Herron and Heirtzler*, 1967].

In the Atlantic Ocean, the agreement is not as good because the pole chosen was the one for the South Pacific. South of 30°N, however, the agreement is fair. North of 30°N, there is disagreement as noted by *Morgan* [1968], and this should be expected as the relative movement of Eurasia away from America cannot be the same as the movement of Africa away from America. Africa and Eurasia are now involved in the opening of the Indian Ocean around a pole situated near 26°N and 21°E. The small but systematic difference between the poles determined for South Pacific and South Atlantic and the poles determined from North Pacific and North Atlantic might suggest a small differential movement of North America and South America.

The fact that the spreading in the Indian Ocean does not obey a single pattern of rotation accounts for the complexity of the physiography of this ocean and can be taken into account when one recognizes the presence of the Java trench north of the only fast spreading ridge segment running essentially east-west [*Le Pichon and Heirtzler*, 1968]. In spite of these complications, however, the main movement in the Indian Ocean is one of opening around a pole situated somewhere near the present location of Libya. The Alpine fault and Macquarie ridge must result from the conflicting movement of the Indian and Pacific Ocean crustal plates. The absence of a fast spreading ridge around the southern tip of Africa removes one of the major geometrical difficulties posed by the distribution of the mid-ocean ridges.

To summarize, Figure 10 illustrates how the present pattern of relative movement over the world can be described by a few rotations. The main rotations are in the Atlantic and the Pacific (about slightly different poles), with a third major rotation in the Indian Ocean. The rates of angular opening are, however, quite different, 3.6×10^{-7} deg/yr in the Atlantic Ocean and 4.0×10^{-7} deg/yr in the Indian Ocean compared with 10.8×10^{-7} deg/yr in the South Pacific Ocean. Figure 11 also shows that the active trenches run either north–south or east–west in this new system of coordinates, essentially absorbing the movements of the Pacific crustal blocks and of the south Indian Ocean crustal blocks.

Résumé of Spreading History and Continental Movements in Southern Hemisphere Since Lower Mesozoic

The magnetic evidence for ocean floor spreading presented in the companion papers places several restrictions on the allowed paths of continental movements since the break up of Gondwanaland. It is thus possible to synthesize a picture of continental movement in the southern hemisphere since the early Mesozoic.

Paleomagnetic reconstructions by *Irving* [1964] and *Creer* [1965] have the continents of Africa, Antarctica, Australia, India, and South America united and close to the south geographic pole in the Early Permian. *Gough et al.* [1964] show that there has been little change in the paleomagnetic latitude of Africa since the middle of the Mesozoic. They also show evidence of rapid northward movement of Africa during the early Mesozoic and Permian. Studies by *Creer* [1965] suggest that there has not been appreciable change in the paleolatitude of South America since Triassic-Jurassic times but that large northward movements did take place in the Lower and Middle Permian. Investigations on the Triassic-Jurassic lavas that appear in all the Gondwanic continents indicate that the breakup of Gondwanaland had already occurred by this time.

From the study of the magnetic pattern in the Indian Ocean the initial northward movement of the Africa-South America block in Mesozoic-Permian times occurred as a result of spreading about the southwest branch of the mid-Indian ridge. The break from the initial mass started at the Horn of Africa and then opened down the east coast of Africa. At present there is little or no spreading about this branch of the mid-Indian ridge, and, on the basis of paleomagnetic evidence, it appears that it was active during the lower Mesozoic and Permian but that by Jurassic the spreading had mainly ceased. The split in the South American and African continents may have begun in early Mesozoic almost simultaneously with the break away of the African-South American block. Thus, the Argentine and Cape basins were born. The cessation of spreading about the southwest branch of the mid-Indian ridge in Cretaceous and the development of a major part of the Argentine and Cape basins ended the first major phase of spreading in the southern Indian and South Atlantic oceans.

The second phase of spreading involved the further separation of South America from Africa and the northward movement of India in the Indian Ocean. The direction of spreading in the South Atlantic underwent a major change in the Upper Cretaceous (80 m.y.), becoming nearly east–west, and there was little change in the paleolatitudes of either South America or Africa. The Upper Cretaceous also saw the separation of the New Zealand block from Antarctica. The spreading on the west side of the mid-Atlantic ridge was smooth and continuous, and South America was able to drift westward over what was then a large Pacific Ocean. Spreading on the east side of the ridge was not as smooth, and the east–west spreading on that side is not evident until the Early Eocene. Perhaps the restrictions placed on the African block by activity in the Indian Ocean caused this hiatus in the spreading history and resulted in the initial formation of the Walvis ridge. The northward trek of India was accommodated by a major change in the spreading pattern of the Indian Ocean. Spreading on the southwest branch of the mid-Indian Ocean ridge had almost ceased, and it now began to act as a large series of fracture zones that essentially marked the locus of the west coast of India in the northward movement. *Le Pichon and Heirtzler* [1968] suggest that the movement of India was accomplished by spreading about a now subsided east–west striking ridge situated in the Java basin.

The third major readjustment to the spreading in the Indian Ocean occurred at the end of the Eocene (40 m.y.) with the commencement of spreading about the southeast and northwest branches of the mid-Indian Ocean ridge. The readjustment was occasioned by the abutting of the Indian subcontinent against the Asian block. This new stage of spreading resulted in the rapid separation of Australia from Antarctica and Broken ridge from the Kerguelen plateau. Much of the differential movement resulting from different directions and unequal rates of spreading on these two limbs has been absorbed by the Amsterdam fracture zone. Ninetyeast ridge was formed by the differential movement of the blocks on either side of it. A result of the various stages of spreading in the Indian Ocean is that India moved much farther north than Antarctica moved south. Spreading about the southeast branch of the mid-Indian ridge alone does not satisfy the paleomagnetic evidence of high latitudes for Australia during the Permian; it seems likely that the ridge itself has migrated northward. Interaction between the northward movement of Australia and the northwest movement of the New Zealand plateau has probably resulted in the Alpine fracture zone in western New Zealand.. Finally, during the last 10 m.y., the Atlantic, south of 30°N, and the Pacific oceans have been rotating about the same pole, while the Indian Ocean has been rotating about a different pole.

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