Sea-Floor Spreading and Continental Drift[1]

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A geometrical model of the surface of the earth is obtained in terms of rigid blocks in relative motion with respect to each other. With this model a simplified but complete and consistent picture of the global pattern of surface motion is given on the basis of data on sea-floor spreading. In particular, the vectors of differential movement in the 'compressive' belts are computed. An attempt is made to use this model to obtain a reconstruction of the history of spreading during the Cenozoic era. This history of spreading follows closely one previously advocated to explain the distribution of sediments in the oceans.

I. INTRODUCTION

It has long been recognized that if continents are being displaced on the surface of the earth, these displacements should not in general involve large-scale distortions, except along localized belts of deformation. Recent studies of the physiography of the ocean floor [*Heezen*, 1962] and of the distribution of sediments in the oceans [*Ewing and Ewing*, 1964] did not reveal widespread indications of compression or distortion of large oceanic blocks. Consequently, the displacements inferred in the spreading-floor hypothesis of *Hess* [1962] and *Dietz* [1961] should not result in large-scale deformation of the moving blocks. *Morgan* [1968] has investigated the important implications of these observations on the geometry of the displacements of ocean floor and continents. In this paper we try to carry this attempt further and to test whether the more uniformly distributed data on sea-floor spreading now available are compatible with a non-expanding earth. The discussion will be confined to a preliminary investigation of the global geometry of the pattern of earth surface movements as implied by the spreading-floor hypothesis. We use Morgan's exposition of the problem as a basis. Parts of these results were previously reported by *Le Pichon and Heirtzler* [1968] and *Heirtzler et al.* [1968].

Let us assume that large blocks of the earth's surface undergo displacements and that the only modifications of the blocks occur along some or all of their boundaries, that is, the crests of the mid-ocean ridges, where crustal material may be added, and their associated transform faults, and the active trenches and regions of active folding or thrusting, where crustal material may be lost or shortened. Then the relative displacement of any block with respect to another is a rotation on the spherical surface of the earth. For example, if the Atlantic Ocean is opening along the mid-Atlantic ridge, the movement should occur in such a way as not to deform or distort the large bodies of horizontally stratified sediments lying in its basins and at the continental margins. It should not involve large-scale distortion of the African or South American continents. Motion of the African relative to the South American block (one block including the continent and its adjacent basins) should be everywhere parallel to the transform faults [*Wilson*, 1965*a*], which should be arcs of a small circle about the center of this movement of rotation. The angular velocity of rotation should be the same everywhere. This implies that the spreading rate increases as the sine of the distance (expressed in degrees of arc) from the center of rotation and reaches a maximum at a distance of 90° from this center, along the equator of rotation.

Morgan [1968] has shown that the fracture zones in the Atlantic Ocean between 30°N and 10°S are very nearly small circles centered

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TABLE 1. Measured Spreading Rates*

Pacific			Atlantic			Indian		
Latitude	Longitude	Rate, cm/yr	Latitude	Longitude	Rate, cm/yr	Latitude	Longitude	Rate, cm/yr
48N	127W	2.9	60N	29W	0.95	19N	40E	1.0
17S	113W	6.0 (5.9†)	28N	44W	1.25 (1.3†)	13N	50E	1.0
40S	112W	5.1 (5.3)	22N	45W	1.4 (1.5)	7N	60E	1.5
45S	112W	5.1 (5.1)	25S	13W	2.25 (2.0)	5N	62E	1.5
48S	113W	4.7 (5.0)	28S	13W	1.95 (2.0)	22S	69E	2.2
51S	117W	4.9 (4.8)	30S	14W	2.0 (2.0)	30S	76E	2.4
58S	149W	3.9 (3.6)	38S	17W	2.0 (1.9)	43S	93E	3.0
58S	149W	3.7 (3.6)	41S	18W	1.65 (1.9)			
60S	150W	4.0 (3.4)	47S	14W	1.60 (1.6)			
63S	167W	2.3 (2.8)	50S	8W	1.53 (1.5)			
65S	170W	2.0 (2.6)						
65S	174W	2.8 (2.4)						

* Arctic Ocean: ≈1.0 cm/yr.
Norwegian Sea: ≈1.0 cm/yr.
† Computed from center of rotation determined from spreading rates by least squares.

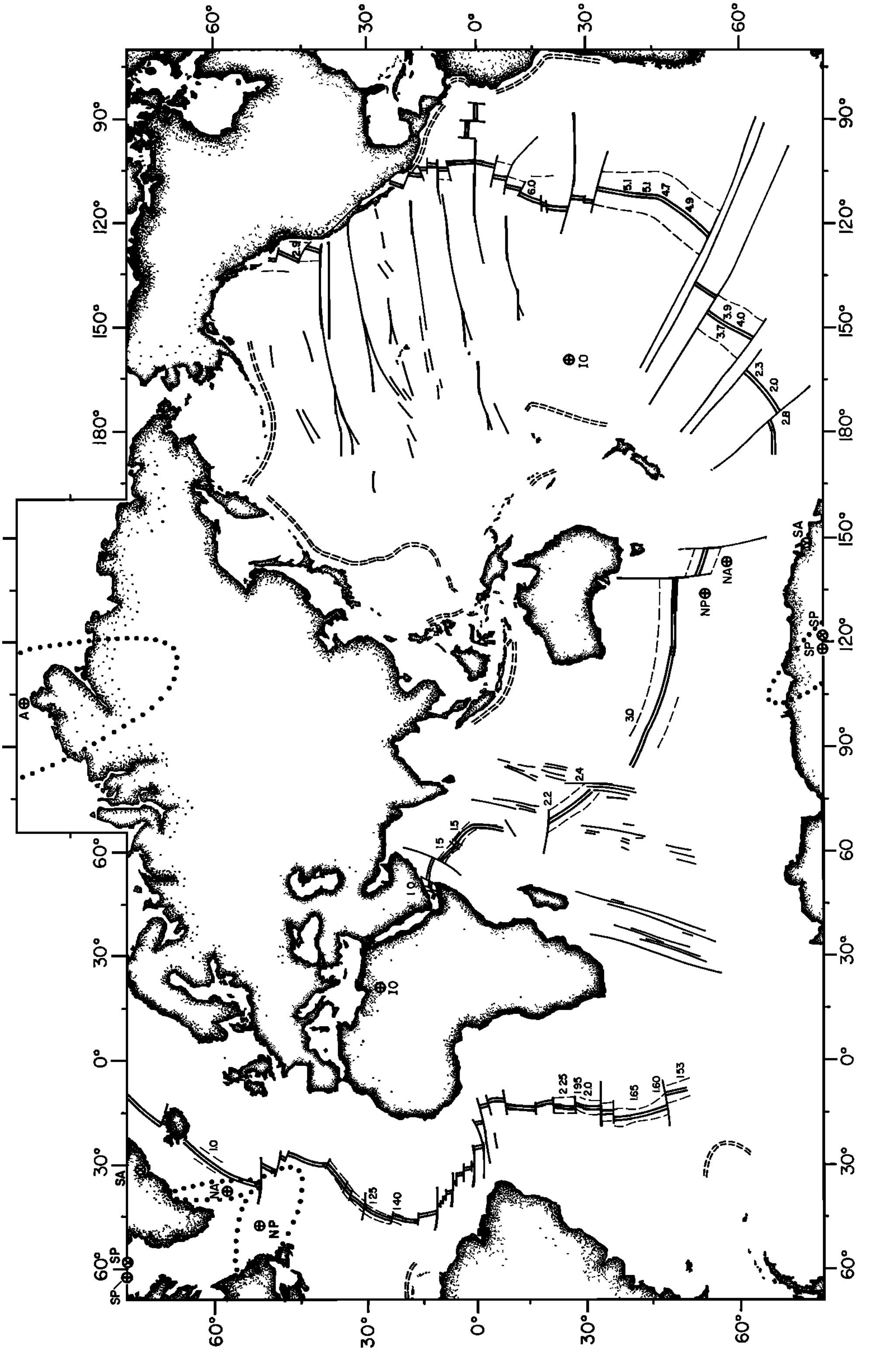
about a point near the southern tip of Greenland and that the spreading rates already determined roughly agree with the velocities required for a movement of opening of the Atlantic Ocean about this point. Thus sea-floor spreading in the Atlantic Ocean does not involve distortion of the oceanic and continental blocks on each side of it. Morgan has shown similarly that the fault systems along the west coast of North America (e.g., the Denali, San Andreas, and Gulf of California fault systems) were compatible with a movement of rotation of the Pacific Ocean floor away from North America about a point also situated near the southern tip of Greenland.

Recent work [*Pitman et al.*, 1968; *Dickson et al.*, 1968; *Le Pichon and Heirtzler*, 1968; *Heirtzler et al.*, 1967, 1968; *Herron and Heirtzler*, 1967; *Herron*, in preparation] has greatly extended our knowledge of the pattern of spreading since the end of the Mesozoic. The locations and extents of the large fracture zones in parts of the North and Equatorial Atlantic and in the Indian Ocean [*Heezen and Tharp*, 1964, 1965], in the North and Equatorial Pacific [*Menard*, 1964], and in the South Pacific [*Pitman et al.*, 1968] are now reasonably well known. These data are adequate for a preliminary examination of the global geometry of continental and oceanic drift deduced from the spreading-floor hypothesis.

We first show that the opening of the South Pacific, the Atlantic, the Arctic, the North Pacific, and the Indian oceans can each be described by a single rotation. The parameters of these rotations are obtained.

Second, we adopt a simple earth model consisting of six large rigid blocks. Using the parameters obtained in the first part, we obtain the vectors of differential motion between blocks along all the boundaries. The picture obtained is in reasonable agreement with physiographic, seismic, and geological data.

Fig. 1. Available data on sea-floor spreading. The axes of the actively spreading mid-ocean ridges are shown by a double line; the fracture zones by a single line; anomaly 5 (≈10 m.y. old) by a single dashed line; the active trenches by a double dashed line. The spreading rates are given in centimeters per year. The locations of the centers of rotation obtained from spreading rates are shown by ×; those obtained from the azimuths of the fracture zones by +. NA stands for North Atlantic; SA for South Atlantic; NP for North Pacific; SP for South Pacific; IO for Indian Ocean; A for Arctic. The ellipses drawn around the NA, NP, SP, and A centers of rotation obtained from the fracture zones are the approximate loci of the points at which the standard deviation equals 1.25 times the minimum standard deviation. The ellipse around the IO center of rotation is too small to be shown. These ellipses indicate how fast the least-squares determination converges.



We then use the same type of analysis to study the movements of continental drift and sea-floor spreading since Mesozoic time. The Atlantic, South Indian, and South Pacific oceans are studied in greater detail. The data suggest a history of episodic spreading directly related to the major orogenic phases.

II. Main Ocean Opening Movements as Determined from Sea-Floor Spreading

Spreading Rates

Vine and Wilson [1965], using *Vine and Matthews'* [1963] hypothesis, first tried to relate the magnetic pattern over the crests of the ridges to the known geomagnetic time scale in order to determine the spreading rate over the last few million years. To date, 31 determinations of spreading rate at the axis of the ridge during Plio-Pleistocene times have been published. The results are listed in Table 1 and shown in Figure 1. The numbers represent the mean spreading rate in centimeters per year on one limb, assuming the motion to be perpendicular to the axis of the ridge and symmetrical about it. The total rate of addition of new crust is equal to twice the spreading rate. The precision of the measurements is probably not better than 0.1 cm/yr. Figure 1 also shows the location of a magnetic anomaly presumed to be 10 m.y. old which marks the outer boundary of the axial magnetic pattern (anomaly 5 of *Heirtzler et al.* [1968]).

The data reveal that the process of addition of new crust is now occurring in all oceans. The spreading rates vary between about 1 cm/yr (in the Arctic Ocean) and as much as 6 cm/yr in the Equatorial Pacific Ocean. Spreading rates have been obtained for all branches of the mid-ocean ridge system except the southwest mid-Indian Ocean ridge; its axial magnetic pattern could not be interpreted simply in terms of the spreading-floor hypothesis [*Vine,* 1966; *Le Pichon and Heirtzler,* 1968]. The number of determinations is now sufficiently large to show that the values of the spreading rate vary rather smoothly and systematically by more than a factor of 2 within a given ocean. The maximum spreading rate is found south of the equator in the Atlantic, Indian, and Pacific oceans. If there are no regions where the earth's surface is destroyed to compensate for the creation of new earth's surface, the earth must then be expanding in an asymmetrical way: the equatorial circumference is increasing faster than any longitudinal circumference. This argument will be explored further in a later section. In any case, the data available suggest a relatively simple pattern of opening of the oceans, the Atlantic and Pacific oceans opening about approximately the same axis and being linked by two oblique openings, one in the Indian Ocean and one in the Arctic Ocean.

Directions of Motion

As indicated earlier, the movement of spreading away from the axes of the ridges should be parallel to the seismically active portions of the transform faults. Figure 1 shows the locations of the major fracture zones over the mid-ocean ridge system according to the sources listed above. The degree of accuracy of mapping is extremely unequal, and large errors may exist in some areas, as south of Australia, for example.

We have two independent sets of data from which to determine the center of rotation: the spreading rates and the azimuths of the transform faults at their intersections with the ridge axis. The mapping of the fracture zones away from the crests of the ridges allows us to determine whether the geometry of the spreading has been the same during the whole geological time required for the creation of these transform faults.

Determination of the Parameters of Rotation

To test the simple geometrical concept of rotation of rigid blocks, we used the following method. For each of the five principal lines of opening (Arctic, Atlantic, Indian, South Pacific, and North Pacific), if the data were adequate, we obtained by least-squares fit (1) the location of the center of rotation (or its antipode) and the angular velocity best fitting the spreading rates and (2) the location of the center of rotation best fitting the azimuths of the transform faults at their intersection with the ridge axis. The numerical method of fitting minimized the sum of the squares of the residuals of the normalized spreading rates (i.e., actual spreading rate divided by maximum spreading rate) in the first case and of the azimuths in the second case. (See in the appendix an outline of the numerical method of computation.) The data for regions in the Atlantic and South Pacific oceans near the equator of rotation are sufficient to allow a good determination of the maximum spreading rate (respectively 2.05 and 6 cm/yr). For the Indian, North Pacific, and Arctic oceans, the data are inadequate to allow a determination of the center of rotation by use of the spreading rates only.

The values of the standard deviation for each fit and the importance of the disagreement between the locations of the centers of rotation obtained by the two methods give a first indication of how well the movement of spreading can be approximated by a single rotation. In addition, a graphical test was made in which the properties of the Mercator projection were used. If the axis of rotation is the axis of projection for a Mercator map, the transform faults should be along lines of latitude, the ridge axis should in general be along lines of longitude (as spreading generally occurs perpendicularly to the ridge crest), and the distance to a given anomaly should be constant on the map (as it varies as the sine of the distance from the center of rotation). This test was made, with the help of a digital computer with plotter, by rotating the pole of the system of coordinates to the center of rotation determined by least squares and by replotting the map in this new coordinate system.

The results of the least-squares determinations of the centers of rotations are listed in Table 2 and their locations are shown in Figure 1. The parameters of rotation adopted for the calculation of the movements of the different blocks are underlined in the table. The rate is given in units of 10^{-7} deg/yr (1° in 10 m.y.), which is nearly equal to 1 cm/yr at the equator of rotation (0.5 cm/yr for the spreading rate). The graphical tests of the calculations of the centers of rotation are shown in Figures 2, 3, and 4, which should be compared with Figure 1. In these figures the latitude is the distance in degrees from the equator of rotation.

The South Pacific Ocean

Spreading rates. The spreading rates used for the determination of the South Pacific ro-

TABLE 2. Centers of Rotation Obtained by Least-Squares Fitting

	Latitude	Longitude	Number	Standard Deviation	Angular Rate, 10^{-7} deg/yr
	South Pacific (Antarctica-Pacific)				
From fracture zone	<u>70S</u>*	<u>118E</u>	6	4.5†	<u>10.8</u>
From spreading rate	68S	123E	11	0.058‡	10.8
	Atlantic (America-Africa)				
From fracture zone	<u>58N</u>	<u>37W</u>	18	2.9†	<u>3.7</u>
From spreading rate	69N	32W	9	0.065‡	3.7
	North Pacific (America-Pacific)				
From fracture zone	<u>53N</u>	<u>47W</u>	32	5.7†	<u>6.0</u>
	Indian Ocean (Africa-India)				
From fracture zone	<u>26N</u>	<u>21E</u>	5	0.6†	<u>4.0</u>
	Arctic Ocean (America-Eurasia)				
From fracture zone	<u>78N</u>	<u>102E</u>	4	9.1†	<u>2.8</u>

* Underlined values are those used in computing movements of different blocks.
† Deviation of measured from computed azimuths, in degrees.
‡ Deviation of measured from computed normalized spreading rates (actual spreading rate divided by maximum spreading rate).

tation are listed in Table 1 and compared with the spreading rates computed for the center of rotation so determined. They were obtained from *Pitman et al.* [1968] and E. M. Herron (in preparation). Note the good agreement between theoretical and measured spreading rates in Table 1.

Fracture zones. The azimuths of the transform faults used for the determination of the center of rotation are compared in Table 3 with the theoretical azimuths. The determination depends heavily on the azimuth of the southernmost fracture zone. It is difficult to know which part of the standard deviation of 4.5° is due to errors in mapping the fracture zones and reading their strikes. However, the agreement between the two methods of determination is good, since the distance between the two points is only 200 km (see Figure 1).

Graphical test. Figure 2 is a graphical test of this determination obtained by rotating the pole of projection from the present geographic pole to 69°S, 123°E, which was an early determination of the center of rotation. In this new projection the fracture zones in the South Pacific lie along lines of latitude. Figure 2 also shows the locations of three key anomalies, numbers 5, 18, and 31, which are specifically 10, 45, and 70 m.y. old according to the *Heirtzler et al.* [1968] provisional time scale. Anomaly 31 approximately marks the outer limit of the correlatable pattern of magnetic anomalies covering the present system of mid-ocean ridges. Figure 2 shows, independently of the latitude or of the side of the crest on which the anomaly is situated, that the longitudinal separation between any of these key anomalies and the axis is nearly the same. The agreement would be slightly better if the center of rotation used had been the one listed in Table 2 (70°S, 118°E).

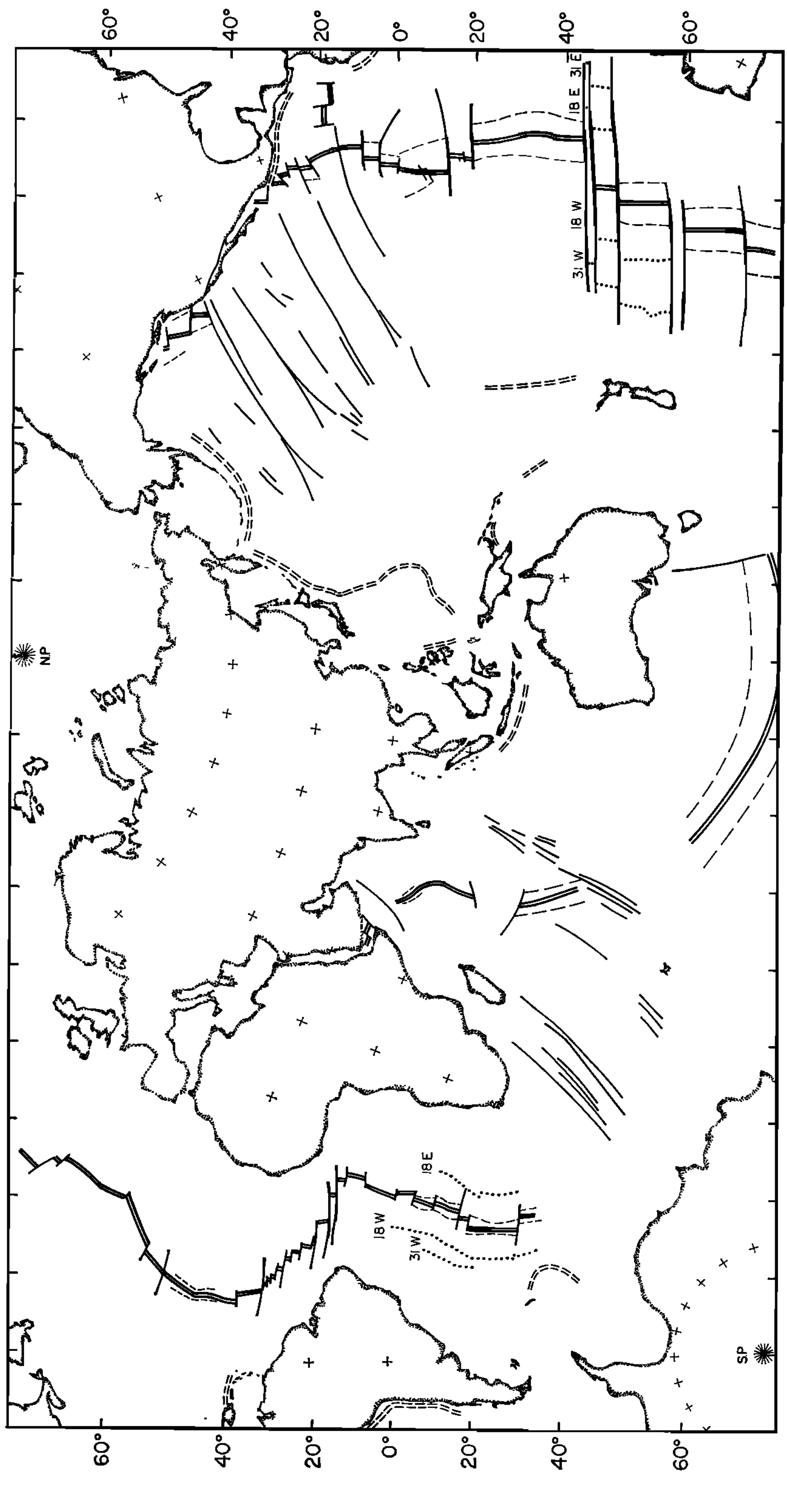
We can conclude that the movement of rotation now characteristic of the South Pacific has been prevalent during the time necessary for the opening of the ocean, i.e., presumably since the end of the Mesozoic. The center of rotation is near 70°S, 118°E, and the angular rate of opening is 10.8×10^{-7} deg/yr. This rotation is not much different from the rotation now characteristic of the North Pacific, as the ridge crests and transform faults in the Gulf of California and north of the Mendocino fracture zone are aligned nearly along lines of longitude and latitude, respectively, in Figure 2. It disagrees, however, by about 30° from the set of 'fossil' fracture zones mapped by *Menard* [1964] in the North and Equatorial Pacific. Note in particular that north of the intersection of the East Pacific rise with the West Chile ridge, the anomaly 5 lines (10 m.y.) are in most cases perpendicular to the 'fossil' fracture zones and oblique to the now active transform faults. Thus, apparently, the pattern of spreading in the North and Equatorial Pacific has changed in the last 10 m.y. and now agrees more closely with that prevailing in the South Pacific. The converging movements of spreading in the North and South Pacific prior to 10 m.y. ago must have resulted in relative compression west of the ridge along a line corresponding to the Tuamotu ridge and in relative extension along a line corresponding to the Chile ridge. Consequently, there should now be little if any spreading at the axis of the Chile ridge. *Herron and Heirtzler* [1967] have attributed the existence of the extensional Galopagos rift zone to a similar process.

Figure 2 also shows that the movement of separation of America away from Africa is about approximately the same axis of rotation as the opening of the South Pacific. (See how the two anomaly 18 lines parallel each other in this projection.)

The Atlantic Ocean South of the Azores: Rotation of America away from Africa

If there is no differential movement between South and North America, the movement of the whole American continent away from Africa should be reducible to a single rotation. On the other hand, because this movement may be different from the movement between Eurasia and the Greenland-America block, the movement between Africa and America can be

Fig. 2. The pole of projection has been shifted to the South Pacific center of rotation (69°N, 157°W). The continent outlines, ridge crests and fracture zone locations, and the location of anomalies 5, 18, and 31 were digitized from the original of Figure 1, which was traced on the World Map of the U. S. Navy Oceanographic Office (scale of 1/39,000,000 at the equator). The outlines of the continents north of 80°N or south of 70°S are not as accurate, being traced by hand in each case from an atlas.


60°
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18 W
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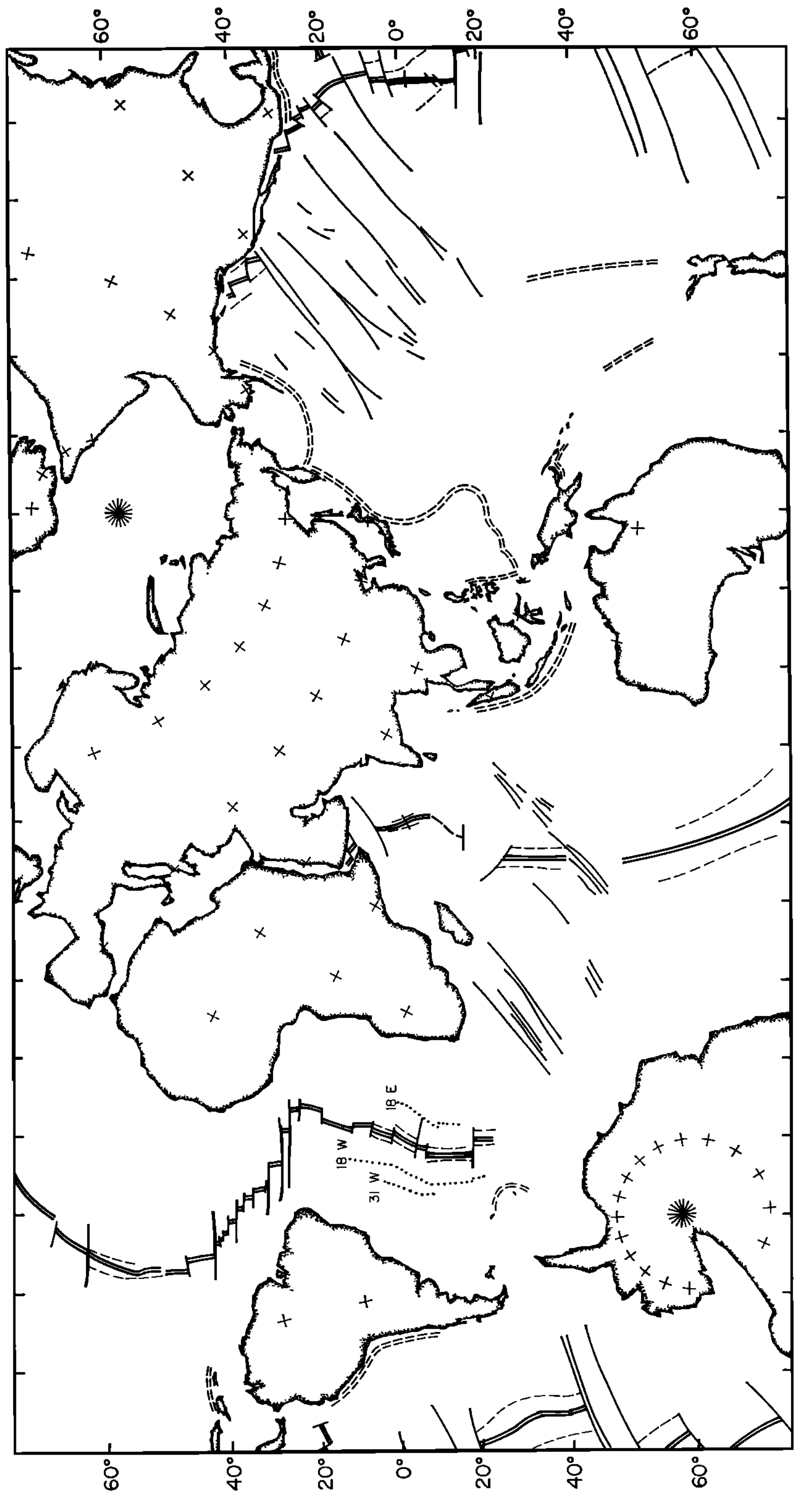

Fig. 3. The pole of projection has been shifted to the Atlantic Ocean center of rotation (58°N, 37°W).

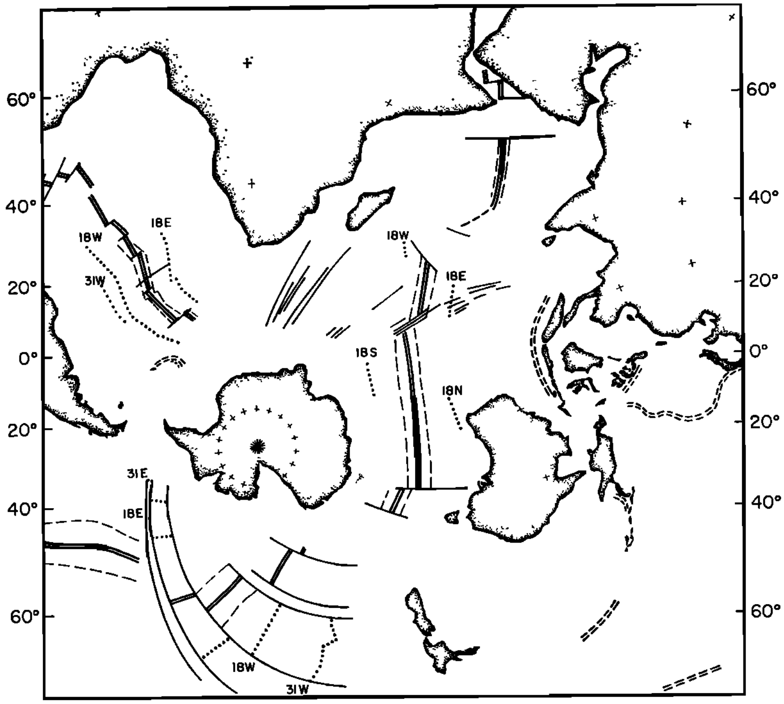

Fig. 4. The pole of projection has been shifted to the Indian Ocean center of rotation (26°N, 21°E).

deduced only from the part of the mid-Atlantic ridge south of the Azores. North of the Azores, as we will see later, the mid-Atlantic ridge belongs to the Arctic system, which also includes the Arctic ridge, the Norwegian ridge, and the Reykjanes ridge, and determines the movement of the Greenland-America block away from Eurasia.

Spreading rates. The published spreading rates for the area south of 40°N used for the determination of the movement of rotation are listed in Table 1 and compared with the theoretical spreading rates. The two rates for the area north of the equator are from *Phillips* [1967]. All the others, for the area between 25°S and 50°S, are from *Dickson et al.* [1968]. Because of the rapid decrease in spreading rate south of 30°S, the equator of rotation has to be near 15°S–20°S as in Figure 2, and the center of rotation best fitting the spreading rates is near 69°N and 32°W. However, this determination is mostly based on data from the South Atlantic, where the true trend of the ridge crest and of the magnetic anomalies is poorly known.

Fracture zones. The reliable data on the azimuths of the fracture zones at their intersection with the ridge crest are for the area between 30°N and 8°S. A list of 18 transform faults in this area given by *Morgan* [1968] was used in computing the best center of rotation giving a point near 58°N, 37°W. Morgan arrived at the same location by using a slightly different method. The distance between this center of rotation determined from fracture zones mostly in the North Atlantic and the center of rotation obtained from spreading rates mostly in the South Atlantic is about 1200 km. It is probably too large to be explained by errors in determinations of spreading rates and can possibly be attributed to some small differential movement between North and South America. The question will be resolved when good mapping of the fracture zones is available for the South Atlantic.

Graphical test. Figure 3 shows that, when the origin of coordinates is rotated to 58°N, 37°W, the fracture zones between 30°N and 10°S are nearly exactly along lines of latitude as required for a movement of rotation around

TABLE 3. Azimuths of Fracture Zones Used for Least-Squares Fitting*

South Pacific			Indian Ocean			Arctic Ocean		
Latitude	Longitude	Azimuth	Latitude	Longitude	Azimuth	Latitude	Longitude	Azimuth
56S	122W	117 (114†)	12N	46E	35 (34†)	82N	12W	132 (131†)
56S	124W	118 (115)	13N	50E	30 (30)	71.5N	12W	125 (116)
57S	141W	121 (121)	9N	55E	32 (32)	66.5N	20W	98 (110)
62S	152W	123 (128)	15N	60E	24 (23)	52N	35W	96 (101)
63S	160W	125 (131)	18N	61E	19 (19)			
65S	170W	141 (137)						

* Azimuths of fracture zones for the Atlantic Ocean and the North Pacific Ocean are as listed by *Morgan* [1968].

† Computed from center of rotation determined from fracture zones by least squares.

this point. But the longitudinal distance to anomaly 18 in the South Atlantic decreases toward the south instead of staying constant. In Figure 2, on the contrary, the longitudinal distance to anomaly 18 is constant with latitude, but the fracture zones north of the equator do not follow lines of latitude. This is further evidence for some small differential movement between North and South America.

We conclude that although there is some evidence for differential movement north and south of the equator, the data suggest that a single rotation around a point near the southern tip of Greenland, at a rate of 3.7×10^{-7} deg/yr, describes the movement of America away from Africa as a good first approximation.

The Arctic Opening from the Azores to the Lena River Delta: Movement of Eurasia away from the Greenland-America Block.

It is assumed that Eurasia, on one hand, and Greenland-America, on the other, are moving as rigid units. Their movement of separation should then be a single rotation produced by spreading along a system of ridges going from the shelf north of the Lena River delta (northern Siberia) to the Azores and including the Arctic ridge. Recent, mostly still unpublished data have indicated that this system is actively spreading at a rate of about 1 cm/yr in the Arctic according to *Demenitskaya and Karasik* [1967] and *Ostenso and Wold* [1967], about 1 cm/yr in the Norwegian Sea according to *Heirtzler et al.* [1967], and 0.95 cm/yr over the Reykjanes ridge according to *Pitman and Heirtzler* [1966].

Fracture zones. The published data on exact trends of the fracture zones are still rare; the four given in Table 3 come from *Johnson* [1967] for 53°N, *Heirtzler et al.* [1967] for 66° and 71°N, and *Sykes* [1965] for 82°N. The abrupt change of 27° between the azimuths of the faults at 71°N and 66°N implies some important distortion between 71°N and 66°N. This distortion may be related to the presumed zone of extension which includes the Bresse and Limagne in southern France, the Rhine graben (most active in Oligocene time [*Cogné et al.*, 1966]), and possibly the North Sea subsiding zone [*Closs*, 1967]. In the absence of more adequate data, a single center of rotation was obtained from these four fracture zones for the whole Arctic system, at 78°N and 102°E, with a standard deviation of 9.1°. This preliminary fit gives a maximum deviation of 12° between measured and computed azimuths (see Table 3). A rate of rotation of about 2.8×10^{-7} deg/yr was chosen on the basis of the rate of spreading over the Reykjanes ridge, account being taken of the 60° angle between the ridge axis and the transform fault at 53°N.

Graphical test. Figure 5 is a world map in which the pole of the system of coordinates has been rotated to 79°N, 111°E, which is the center of rotation determined by Morgan for the 'fossil' system of fracture zones in the North Pacific. It is slightly different from the 78°N, 102°E, center of rotation determined

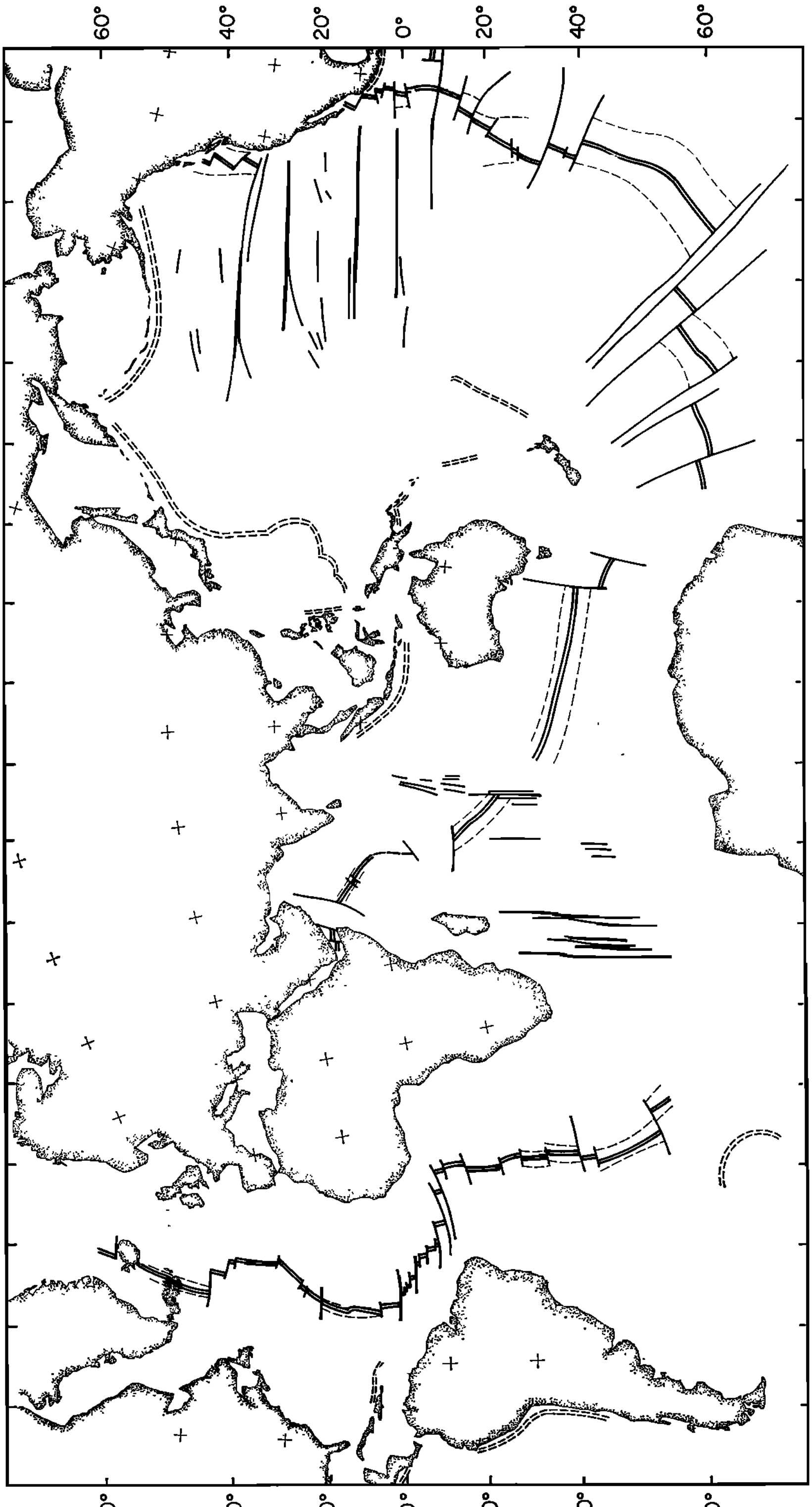

Fig. 5. The pole of projection has been shifted to the center of rotation of the 'fossil' Pacific fracture zones (79°N, 111°E).

for the Arctic system of rotation. However, Figure 5 is useful in evaluating the movement involved in the opening of the Arctic system. The fracture zones between 53°N and the Azores are poorly determined, and their trend might be different from the ones shown in Figures 1 to 5. A much better estimate of the movement involved in the separation of America from Eurasia will be possible when the new data are published. The present determination is reasonable as a first approximation, however, and it is interesting that it falls close to the center of rotation determined by *Bullard et al.* [1965] for the best fit of Greenland to Europe (73°N, 96.5°E).

The Movement of the North Pacific Ocean away from North America

Wilson [1965*a*] pointed out that the San Andreas fault could be understood as a ridge-ridge type of transform fault between the Gorda and Juan de Fuca ridges and the termination of the East Pacific rise in the Gulf of California. Similarly he noted that the Denali and Queen Charlotte Island fault systems could be understood as a ridge-arc type of transform fault connecting the Juan de Fuca ridge to the Aleutian arc. Thus the resulting movement should be a movement of rotation of the Pacific Ocean floor away from North America, the direction of motion being given by the azimuths of the transform faults.

Fracture zones. Morgan [1968] has compiled a list of the azimuths of this system of faults at 32 locations between 60°N and 24°N. Using this list, he found the center of rotation by least squares to be at 53°N, 47°W. The standard deviation of 5.7° is not excessively large, considering that the measured azimuths range over 29° from 154° to 125° and the computed ones from 145° to 130°. The difference between this location and the one of the center of rotation determined by Morgan (53°N, 53°W) may come from his elimination of some of the azimuths listed in his paper.

Morgan did not include the Blanco fracture zone in his list, as he considered that the Juan de Fuca and Gorda ridge blocks were moving independently of the North America block. Comparing the trends of the fracture zones at both ends of the Juan de Fuca ridge with the trends predicted by the 53°N, 47°W, center of rotation shows a systematic disagreement of 20°, which implies compression and deformation of the continent adjacent to this block.

Velocity of rotation. The only locations where spreading rates have been determined in the North Pacific are over the Juan de Fuca–Gorda blocks, where the spreading rate at 46°N is 2.9 cm/yr [*Vine*, 1966]. However, as there is presumably some differential movement between the ocean block and the continental block east of the ridge, the actual rate of angular rotation of the Pacific Ocean floor away from North America should be somewhat smaller than 6.5×10^{-7} deg/yr (i.e., $(2.9 \text{ cm/yr} \times 2 \times \cos 20°)/(\sin 50° \times 1.11 \times 10^7 \text{ cm})$, 50° being approximately the distance to the center). On the other hand, *Rusnak et al.* [1964] have estimated the total displacement involved in the creation of the Gulf of California as between 300 and 450 km. This displacement is supposed to have occurred since late Miocene time (which is in reasonable agreement with the date of anomaly 5, i.e., 10 m.y.) and would lead to an average rate of rotation of 3.5 to 5.2×10^{-7} deg/yr if the movement started 10 m.y. ago. For the global calculations of the displacements, a rate of 6×10^{-7} deg/yr was chosen for the rotation of the Pacific Ocean away from North America around 53°N, 47°W, which implies a rate of slippage of about 5 cm/yr along the San Andreas fault. This estimate agrees closely with the present velocity of regional shear strain, which is about 6 cm/yr [*Hamilton and Myers*, 1966].

The Indian Ocean

Figure 1 and Table 1 show that the data on spreading in the Indian Ocean cannot be simply explained by a single rotation of the northeast Indian Ocean away from the southwest Indian Ocean. The spreading rates increase continuously from the Red Sea–Gulf of Aden region to south of Australia while the trends of the fracture zones change abruptly south of the Rodriguez fracture zone near 20°S, being apparently influenced by the junction with the southwest branch of ridge over which no spreading rate has yet been determined. Unfortunately, the fracture zones south of Australia are poorly known, and it is not possible to determine directly a center of rotation of Australia away from Antarctica. On the other hand, the fracture zones within the Gulf of Aden, including the Owen fracture zone [*Laughton*, 1966], are better known and can be used to determine the movement of rotation of the northern Indian Ocean away from the Africa block [*Le Pichon and Heirtzler*, 1968].

Fracture zones. The five azimuths used for the determination of the center of rotation were obtained from Figure 14 of Laughton; two were from the Gulf of Aden, three from the Owen fracture zone. They are listed in Table 3 and compared with the computed values for the center of rotation at 26°N, 21°E. The standard deviation between measured and computed azimuths is only 0.6° in spite of the fact that the azimuths range over 16°, from 19° to 35°. These trends are in good qualitative agreement with the trends of the fracture zones over the Carlsberg ridge as shown in the *National Geographic Magazine* diagram of the Indian Ocean (based on Heezen and Tharp's revised interpretation). On the basis of the fracture zones, it is not possible to distinguish between movements on each side of the Owen fracture zone. From Table 1 it can be seen that the spreading rates for the Gulf of Aden (1 cm/yr, W. Ryan, in preparation) and for the Carlsberg ridge (1.5 cm/yr) do not indicate large differential movement along the Owen fracture. On the other hand, it is not possible to reconcile the trends of the Rodriguez and Amsterdam fracture zones with the rotation around 26°N, 21°E.

Graphical test. In the test, illustrated in Figure 4, the pole of the system of coordinates has been rotated to 26°N, 21°E. Although the agreement with a single movement of rotation around this pole is quite good for the area north of the Rodriguez fracture zone, south of the point where the three branches of ridge join together the pattern of fracture zones assumes new trends. This can be explained if there is some movement of opening along the southwest branch of the ridge. The movement of rotation of Australia away from Antarctica will then be the sum of the rotation of Africa away from Antarctica and Arabia-India away from Africa. Le Pichon and Heirtzler have noted on the basis of the anomaly pattern that, if there is active spreading on the southwest mid-Indian Ocean ridge, it is unlikely to exceed 1 cm/yr. In a later section we will try to reconcile these conclusions. Le Pichon and Heirtzler have also mentioned the possibility of some small differential movement between the northwest and northeast Indian Ocean along the Ninetyeast ridge (which is slightly seismic, L. R. Sykes, personal communication). As a first approximation we conclude that the relative movement of the whole northern Indian Ocean (including Australia) away from Africa occurs around a point near 26°N, 21°E. The angular rate of opening is about 4×10^{-7} deg/yr.

III. Global Geometry of Present Earth Surface Displacements

In the preceding section, the system of large crustal displacements has been reduced as a first approximation to five ocean-opening movements. Each movement has been described as a single rotation of one rigid block away from the other, and the parameters of rotation, i.e., the axis of rotation and the rate of angular rotation, have been determined (see Table 2). Figure 1 summarizes the data available on sea-floor spreading, showing the two locations at which each axis of rotation pierces the earth's surface. Those movements result from the addition of new crustal material at the crests of the mid-ocean ridges, so that, if the earth is not expanding, there should be other boundaries of crustal blocks along which surface crust is shortened or destroyed. In the spreading-floor hypothesis, these boundaries are the active trenches and Tertiary mountain belt systems. However, if the earth is not expanding, what is the mechanism which results in this pattern of movements? It is difficult to imagine large-scale convection currents rising immediately below the crests of the ridges, with elongated conical shapes on the ridges, rates of motion increasing from zero near the axis of rotation to a maximum under the equator of rotation, and staggered sections offset along transform faults. Rather the pattern of opening of the oceans seems to be the response of a thick lithosphere (able to transmit stress along great distances), which breaks apart along lines of weakness, to some underlying state of stress as variously favored by *Elsasser* [1968], *McKenzie* [1967], *Morgan* [1968], and *Oliver and Isacks* [1967]. *Carey* [1958] and more recently *Heezen and Tharp* [1965] have argued that a possible cause of this state of stress is the expansion of the earth, a cause which does not require that the crust be destroyed as rapidly as it is created at the crests of the ridges.

The Expansion Hypothesis

Without entering into other considerations, we will consider first the pattern of deformation of the earth's surface, assuming that there are no zones of compression. We can then easily find, with the data in Table 2, how much the circumference of any great circle on the surface of the earth is increasing per year. Ideally, each great circle should expand at the same rate, so that the earth's surface maintains its nearly spherical shape. Such an idea can be tested rapidly by considering Figure 2, in which the axis of projection is the axis of rotation of the South Pacific; it is also close to the Atlantic and North Pacific axes of rotation. Note that in the projection of Figure 2 most of the spreading occurs about axes which run north-south, whereas very few ridge axes run east-west. The great circle formed by the equator of rotation in Figure 2 expands at a rate of about 17 cm/yr (4 at the mid-Atlantic ridge, 12 at the East Pacific rise, and 1.5 at the Carlsberg ridge). On the other hand, the great circles of longitude of Figure 2 are parallel to the crests of the Atlantic and Pacific ridges and would at most intersect the Arctic and South Indian Ocean ridges. The resulting rates of expansion vary between 0 and 7 cm/yr. There is no evidence for important pole migration during the last 10 m.y., yet the equator of rotation in Figure 7 would have increased its circumference by 1700 km and some of the great circles of longitude would not have expanded. This implies a differential expansion of as much as 270 km between the average radius along extreme great-circle circumferences and possibly as much as 500 km between individual radii. It is unacceptable, and it becomes even more so when we recognize that the present pattern of spreading has prevailed during the whole Cenozoic era. Consequently, in the expansion hypothesis, we have to assume some compensating large-scale processes of earth's surface shortening by compression or thrust to maintain the nearly spherical surface of the earth. The expansion hypothesis then loses most of its appeal. Other strong arguments have previously been advanced against the expansion hypothesis [e.g., *Runcorn*, 1965], and it will not be considered further here.

This discussion has led us to recognize that the axes of rotation of spreading which have prevailed during the Cenozoic are not randomly distributed. They have maintained a systematic preferred orientation. In particular the two major openings, in the Atlantic and Pacific oceans, have their centers of rotation within 15° of each other. This observation suggests that a simple pattern of the primary state of stress has continued over the last 60 m.y. (along the lines of latitude of Figure 2). The axis of revolution is close to the axis of rotation of the movements of spreading ($\approx$60°N and 50°W).

Determination of the Movements between Blocks

If we assume that the earth is spherical and that the length of its radius does not change with time, we can then proceed to the complete determination of the movements of the major crustal blocks relative to each other. This, of course, presupposes the determination of the boundaries of the blocks, other than ridge crests, i.e., the lines of compression or shear between blocks. It is further necessary to assume that all blocks, and consequently all ridge crests and other boundaries, may migrate over the surface of the earth (which is another difficulty involved in the hypothesis of convection currents rising immediately below the ridge crests). To make the problem entirely determinate, we divide the earth's surface into six rigid blocks (as compared with the twenty blocks used by Morgan) which stay undeformed except at their boundaries, where surface may be added or destroyed. These simplifications will lead to a mathematical solution which can be considered a first-approximation solution to the actual problem of earth's surface displacements.

Figure 6 shows the five boundaries (double lines) of the six blocks and the names adopted for each. Subsidiary blocks, not used in the computation, are shown by dashed line. Two of these, the Fiji and Philippines basins, can be understood as providing the mean of absorbing the differential movement between two large blocks along two nearly parallel boundaries, instead of only one. The Caribbean block presumably absorbs whatever differential movement there may be between the North and

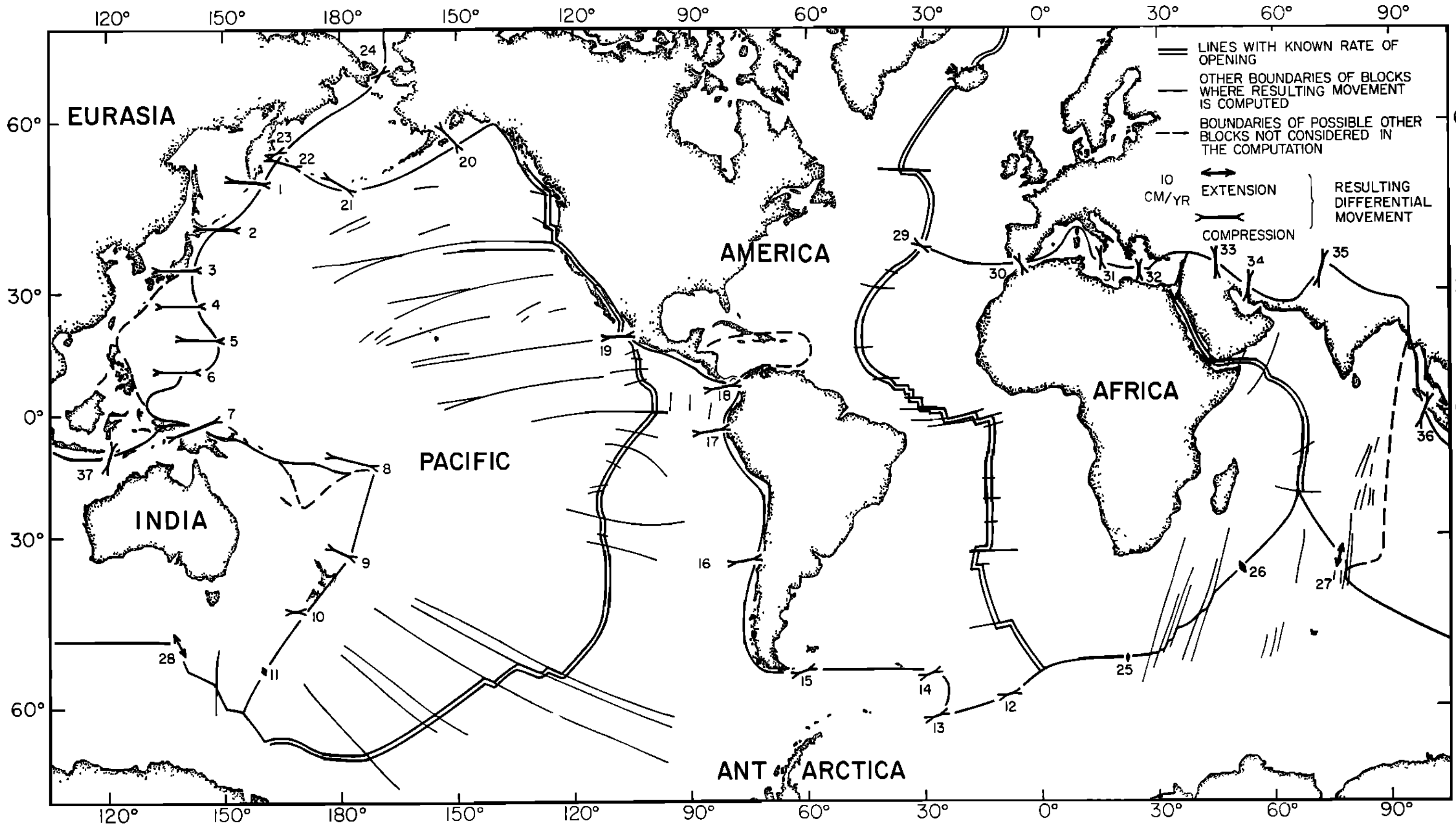

Fig. 6. The locations of the boundaries of the six blocks used in the computations. The numbers next to the vectors of differential movement refer to Table 5. Note that the boundaries where the rate of shortening or slippage exceeds about 2 cm/yr account for most of the world earthquake activity.

South American blocks. In the Indian Ocean, the Ninetyeast ridge may allow some differential movement between the northwest and northeast Indian blocks. Except possibly for the last, none of these subsidiary boundaries would significantly affect the general picture obtained here. The Pacific is the only entirely oceanic block. Eurasia is considered to be a single block (except for India and Arabia), and an arbitrary boundary passes between Alaska and northeastern Siberia.

The resulting instantaneous rotational vector between two blocks can be obtained from the geometrical or vector sum of the rotational vectors of the blocks. These can be obtained from the five rotational vectors previously determined (the five whose parameters are underlined in Table 2). For example, the America-Antarctica vector is the sum of the Pacific-Antarctica and America-Pacific vectors, and the India-Antarctica vector is the sum of the four vectors: Pacific-Antarctica, America-Pacific, Africa-America, and India-Africa. The more vectors that are involved in the sum, the greater is the probable inaccuracy. Also, the sums involving the America-Pacific and America-Eurasia vectors may be less accurate than the others. Table 4 lists the parameters of seven resulting rotational vectors. Tables 2 and 4 were used to compute the vectors of differential movement at 37 locations along the boundaries of the six blocks. The results are shown in Figure 6 and listed in Table 5.

It is important to realize that the number of blocks is chosen in such a way that the problem can be solved. The initial data are the five known movements of opening of the oceans, shown by a double line in Figure 6. The two rotations corresponding to spreading at the axes of the southwest and southeast mid-Indian Ocean ridges are not known and will be determined by the computation. Note that if these two rotations were known, the problem would be overdetermined. This provides a severe test of the computation, as the computed rotations should indicate extension, not compression, over the southeast and southwest mid-Indian Ocean ridges, and directions and rates should agree with the physiographic and magnetic data. Although the axis of a spreading ridge is a well-defined block boundary, the locations of the other boundaries are not as well defined. The choice is guided by the seismic and physiographic data. Active deep-sea trenches and the Alpine-Himalayan mountain belt are obvious choices. If other boundaries than the ones indicated by single full lines in Figure 6 are chosen, the resulting vectors of differential movement will be different, but not the relative vectors of rotation. By using Tables 2 and 4, we can consequently rapidly estimate the effect of choosing somewhat different nonspreading boundaries. Finally, as mentioned earlier, the dashed lines represent boundaries along which it appears that some differential movement occurs. But the data available do not allow a unique determination of the movement along them.

TABLE 4. Instantaneous Centers of Rotation Deduced from Table 2

	Latitude	Longitude	Rate,* 10^{-7} deg/yr
America-Antarctica	79.9S	40.4E	−5.44
Africa-Antarctica	42.2S	13.7W	+3.24
India-Antarctica	4.5S	18.1E	+5.96
India-Eurasia	23.0N	5.2W	−5.50
India-Pacific	52.2S	169.2E	−12.3
Eurasia-Pacific	67.5S	138.5E	−8.15
Africa-Eurasia	9.3S	46.0W	−2.46

* Positive value indicates extension; negative, compression.

Vectors 1 to 6 represent differential movement between Eurasia and Pacific. They are perpendicular to the trench system (corresponding to pure compression or thrust) and have magnitude of 8 to 9 cm/yr. Vectors 4 to 6 would have a different direction and a smaller magnitude if part of the differential movement were absorbed on the west side of the Philippines basin.

Vectors 7 to 11 represent differential movement between the Indian and Pacific blocks. These results may be affected by a possible error in the India-Antarctica rotational vector as discussed later. However, the results obtained get some support from a recent study of deep earthquake focal mechanisms of *Isacks et al.* [1967]. Vectors 7 and 8 indicate mostly strike-slip motion at a rate of 9 to 11 cm/yr along the east-west boundary, from New Guinea to the northern hook of the Tonga trench. Vector 8 also indicates pure compression or thrust in the main part of the Tonga trench. If part of

TABLE 5. Computed Differential Movements between Blocks as Given in Figure 6

	Latitude	Longitude	Rate,* cm/yr	Azimuth	Location
			Eurasia-Pacific		
1.	51N	160E	−7.9	99	Kurile Trench
2.	43N	148E	−8.5	93	Kurile Trench
3.	35N	142E	−8.8	91	Japan Trench
4.	27N	143E	−9.0	91	Japan Trench
5.	19N	148E	−9.0	93	Mariana Trench
6.	11N	142E	−8.9	91	Mariana Trench
			India-Pacific		
7.	3S	142E	−11.0	69	New Guinea
8.	13S	172W	−9.1	107	N. Tonga Trench
9.	34S	178W	−4.7	113	S. Kermadec Trench
10.	45S	169E	−1.7	89	S. New Zealand
11.	55S	159E	+1.6	339	Macquarie Island
			America-Antarctica		
12.	58S	7W	−2.6	72	Southwest Atlantic
13.	61S	26W	−2.7	68	S. South Sandwich Trench
14.	55S	29W	−3.3	72	N. South Sandwich Trench
15.	55S	60W	−3.7	73	Cape Horn
16.	35S	74W	−5.2	79	S. Chile Trench
17.	4S	82W	−6.0	81	N. Peru Trench
18.	7N	79W	−5.9	80	Panama Gulf
19.	20N	106W	−5.3	83	N. Middle America Trench
			America-Pacific		
20.	57N	150W	−5.3	136	E. Aleutian Trench
21.	50N	178W	−6.2	119	W. Aleutian Trench
22.	54N	162E	−6.3	108	W. Aleutian Trench
			America-Eurasia		
23.	56N	165E	−1.6	68	Aleutian-Kurile Islands
24.	66N	169W	−1.4	62	Alaska-Siberia
			Africa-Antarctica		
25.	53S	22E	+1.5	8	S. Southwest Indian Ridge
26.	37S	52W	+2.7	331	N. Southwest Indian Ridge
			India-Antarctica		
27.	36S	75E	+5.8	17	W. Southeast Indian Ridge
28.	50S	138E	+6.4	333	E. Southeast Indian Ridge
			Africa-Eurasia		
29.	40N	31W	−1.5	117	Azores
30.	36N	6W	−1.9	153	Gibraltar
31.	38N	15E	−2.4	169	Sicily
32.	35N	25E	−2.6	176	Crete
			India-Eurasia		
33.	37N	45E	−4.3	176	Turkey
34.	30N	53E	−4.8	186	Iran
35.	35N	72E	−5.6	193	Tibet
36.	0	97E	−6.0	23	W. Java Trench
37.	12S	120E	−4.9	19	E. Java Trench

* Positive value indicates extension; negative, compression.

the movement is absorbed on the west side of the Fiji basin, as it is in the Philippines basin, the direction of vector 8 will be somewhat different and its magnitude smaller; it will then be more comparable to vector 9, which is representative of the southernmost Kermadec trench. South of the Kermadec trench, one gets closer to the center of India-Pacific rotation (situated somewhat north of Macquarie Island). The magnitude of the vector of differential movement decreases and a strike-slip component appears. The rate of motion is less than 2 cm/yr south of 45°S. The small amount of expansion found near Macquarie Island (vector 11) comes from its location just south of the center of rotation. This disagrees with *Sykes'* [1967] finding of thrust faulting for an earthquake mechanism near Macquarie Island. However, a small change in the location of the India-Antarctica center of rotation could modify this last result.

Vectors 12 to 19 represent differential movement between Antarctica and America. Vectors 12 to 15 along the southern boundary indicate strike-slip motion at a rate of 2 to 4 cm/yr, except along the north-south part of the South Sandwich trench where there is compression or thrust. The location of the southern boundary is somewhat arbitrary but is partly justified by the existence of seismic activity along it (L. R. Sykes, personal communication). The rate of motion exceeds 5 cm/yr at the southern boundary of the active part of the Chile trench (vector 16) and stays between 5 and 6 cm/yr up to the northern end of the Middle America trench. A problem is posed by the Panama continental rise, a filled trench [*Ross and Shor*, 1965] for which the computed rate of differential motion is 5.9 cm/yr. A solution to this problem may have been given by *Herron and Heirtzler* [1967], who were able to show the existence of an east-west Galapagos rift zone which began to form about 7 m.y. ago by north-south spreading at a rate of 2 to 3 cm/yr (see Figure 1). Spreading along the axis of the Galapagos rift zone would change the orientation of vectors 18 and 19 from east to northeast. In this hypothesis, the Panama filled trench, like the filled trench east of the Juan de Fuca ridge [*Ewing et al.*, 1968*a*], is a remnant of the once continuous trench system along the west coast of North America. They were abandoned and filled at the time of the change in the pattern of spreading between 10 and 5 m.y. ago [*Vine*, 1966]. It is also possible that some of the compression is taken up in the Lesser Antilles instead of in the west coast of Panama [*Wilson*, 1965*a*].

Vectors 20 to 22 indicate compression or thrust at a rate of 5 to 6 cm/yr on the eastern part of the Aleutian trench and strike slip on the western part. Vectors 23 and 24 indicate relatively small (1.5 cm/yr), mostly strike-slip motion between Alaska and Eurasia. This computed movement may result partly from errors in the determination of the Arctic center of rotation or may be absorbed by crustal deformation somewhere within Eurasia (Verkhoyansk Mountains) or America.

Vectors 25 to 28 are the only vectors computed for the crests of the mid-ocean ridge system. They are consequently comparable to the available data on spreading along these portions of the mid-ocean ridges. Note that the magnitude and direction of the extensional movement computed is in reasonable general agreement with the data. Vectors 25 and 26 indicate some spreading along the crest of the southwest mid-Indian Ocean ridge, the spreading rate (half of the total movement) increasing progressively from 0.8 to 1.3 cm/yr from southwest to northeast. This combination of small spreading rate and numerous large transform faults might explain the difficulty in recognizing the magnetic pattern and yet account for the well-developed physiography of this ridge [*Le Pichon and Heirtzler*, 1968]. Vectors 27 and 28 also indicate spreading along the axis of the southeast mid-Indian Ocean ridge. The computed spreading rates (2.9 to 3.4 cm/yr) agree well with the measured spreading rate of 3 cm/yr (see Figure 1 and Table 1). The direction of vector 27 also agrees well with the trend of the Amsterdam fracture zone. However, vector 28 seems to have an azimuth disagreeing by about 15° with the apparent trend of the fracture zone. Part of this discrepancy may be due to the existence of differential movement along the Ninetyeast ridge. Part must undoubtedly be due to accumulated errors in the determination of the rotational vectors, as the India-Antarctica rotation is the sum of four different vectorial rotations.

Vectors 29 and 32 represent differential motion between Eurasia and Africa. Vectors 29 and 30 indicate compression at a rate of 1.5 to 1.9 cm/yr along the Azores-Gibraltar ridge and some strike-slip component near the western end. A small error in the location of the center of rotation could change this last result. Vectors 31 and 32 indicate nearly north-south compression at a rate of about 2.5 cm/yr within the Mediterranean. The choice of the boundary within the Mediterranean is somewhat arbitrary, as the Mediterranean boundary probably consists of several zones of compression. This vector, then, would be the resultant of the different partial components.

Vectors 33 to 37 correspond to differential movement between Eurasia and the Indian block. The rate of compression reaches a maximum of 6 cm/yr in the Java trench and is about 5 cm/yr in the Himalayas. However, the same remark should be made for this boundary as for the Mediterranean boundary.

Validity of the Pattern of Motion Obtained

Two serious limitations should be placed on the picture just obtained of the general pattern of motion of large crustal blocks on the surface of the earth. The first is obvious; it comes from the fact that we have been forced to make great simplifications and generalizations in order to solve the problem. The second results from the inadequacy and inaccuracy of parts of the data used to determine the pattern of spreading (e.g., preliminary charts of fracture zones, different methods of determining spreading rates). With more and better data and with a more careful consideration of the geology and the seismicity, a better picture can be obtained.

The principal weakness of this picture is that it ignores the seismic and physiographic evidence indicating differential movement around the Caribbean Sea. An examination of the seismic belt along the Cayman trough and the western part of the Puerto Rico trench shows that it follows exactly a small circle centered on 28°S, 71°W. This is consistent with the idea that this zone acts as a transform fault [*Wilson*, 1965*a*]. The main differential movement, then, is parallel to this zone and perpendicular to the Lesser Antilles trend. It is possible to account for this movement by a small difference in the vectors of rotation for North and South America. Better data on the fracture zones in the Atlantic Ocean will show whether the present seismic activity of the Caribbean results from differential motion between North and South America or whether it corresponds mainly to the thrusting of a Pacific plate toward the east as hypothesized by Wilson.

We have shown, however, that the general pattern of spreading revealed in the last two years gives a geometrically consistent picture of the pattern of motion at the surface of the earth. We see that none of the ridges can be understood as an isolated feature but that each is part of an intricate pattern which transfers new earth's surface from sources, principally the axes of the Atlantic and Pacific ridges, to sinks, most of which are situated along the Pacific western margin and the Alpine-Himalayan belt. The geological history indicates that the major sinks, like the Alpine-Himalayan belt, have been localized in the same regions for periods several times longer than the life of the present mid-ocean ridges. The pattern of movement at the mid-ocean ridge crests is consequently controlled not only by the directions of the driving stress pattern and the locations of zones of weakness where crust may part but also by the locations of the major sinks. In this picture the roles of the Indian and Arctic ridges are to reconcile the geometrical incompatibility of the Atlantic source and the Alpine-Himalayan sink. Indeed, the easiest way to transform a vector of movement into another one having a different orientation is by placing an intermediary zone of spreading between the two. Thus the east-west Atlantic vector of movement is transformed by spreading along the Carlsberg ridge into a north-south North Indian Ocean vector of movement which is perpendicular to the Himalayan sink. Similarly, the east-west East Pacific rise vector of movement is transformed by north-south spreading along the Galapagos rift zone into a southwest-northeast vector of movement which is perpendicular to the Middle America trench. It is possible that similar subsidiary spreading exists in the Philippines basin (J. Ewing, personal communication), the Fiji basin, the South Sandwich basin, the Eastern Mediterranean, etc., transforming the directions of vectors of differential movement from one border to the other.

The pattern of motion obtained reveals that zones of folding and compression have differential rates of motion smaller than about 6 cm/yr, whereas active trenches (zones of thrust) have differential rates larger than 5 cm/yr. The obvious exceptions are the west part of the Puerto Rico trench and the east-west part of the South Sandwich trench, which seem to be mostly characterized by strike-slip motion as are the northern end of the Tonga trench and the western end of the Aleutian trench. It is somewhat puzzling, however, that seismic reflection and refraction do not detect significant structural differences between these two types of trenches (J. Ewing, personal communication). Another point of interest is that, when the rate exceeds 8 or 9 cm/yr, there is a tendency for the system to decouple itself into two parallel systems of trenches, each of which absorbs part of the movement.

Finally, it should be noted that along the Pacific borders the main system of trenches has been a western system since latest Miocene time. However, we will see later that during early Cenozoic time the main Pacific system of trenches probably was along the eastern border (west coast of America).

IV. Sea-Floor Spreading and Continental Drift during the Cenozoic

Relative Time Scale

Vine [1966] and *Pitman* [1967] were able to relate the *Raff and Mason* [1961] and *Peter* [1966] lineations to an over-all magnetic pattern which had been created at the crest of the East Pacific rise by sea-floor spreading. More recently, a series of publications summarized by *Heirtzler et al.* [1968] established the fact that the magnetic pattern covering the whole of the East Pacific rise can also be recognized in the South Atlantic and Indian oceans. Other works, in preparation, have tentatively recognized the pattern in the Labrador and Norwegian seas. In the areas covered by the identified magnetic pattern, which corresponds to the surface of the mid-ocean ridge system, we know the relative age of any portion of crust with respect to another. A numbering system of key anomalies was established by *Pitman et al.* [1968], the numbers increasing with age from 1 at the crest to 32 at the outer limit of the recognizable pattern. Three of these key anomalies are shown in Figures 1 to 4. By rotating the blocks by the amount necessary to superpose a given anomaly and by using the assumptions developed in the preceding section, it is possible to obtain the relative positions of the continents and ocean basins on each side of it at the time this anomaly was created. However, the geological time to which this reconstruction applies is not known.

Absolute Time Scale

Vine [1966] derived an absolute time scale for the magnetic pattern by assuming that the spreading rate had been constant throughout the time required to produce this pattern (about 80 m.y.). The result of this twentyfold extrapolation from the known time scale (3.5 m.y.) proved reasonable, as it agreed with many geological deductions on the age of the mid-ocean ridge system [e.g., *Heezen*, 1962]. Furthermore, this concept of steady movement during a time of the order of 100 m.y. agreed with the original spreading-floor concept of convection currents reaching to the surface. It was difficult to imagine such large-scale convection currents being able to stop and restart, accelerate or slow down, in times as small as a few million years.

Heirtzler et al. [1968] tried by the same approach to derive an absolute time scale. However, when the magnetic patterns in the oceans were compared, it appeared that the relative spreading rates between oceans had shown great and apparently rather abrupt variations. This is illustrated by the inset in Figure 11, which is a figure from Heirtzler et al. showing the distance from an anomaly to the crest in an ocean plotted versus the distance from the same anomaly to the crest in the South Atlantic Ocean. These distances were obtained from type profiles which were sufficiently far from the center of rotation to be representative of the movement of opening. From this figure we can deduce that the ratio between spreading rates in the North and South Pacific was about 1 from anomaly 31 to 24, increased rapidly to more than 3 from anomaly 24 to 18, and decreased again to 0.7 after anomaly 5. No systematic gap in the anomaly pattern was found, however, and it was concluded that if there had been a total interruption of spreading it had to have occurred simultaneously in all oceans. This was considered unlikely. Heirtzler et al. consequently derived their absolute time scale (inset, Figure 11) by assuming a constant spreading rate in the South Atlantic, the ocean which apparently showed the minimum amount of systematic variations of relative spreading rate. This time scale, which is not greatly different from Vine's time scale, was in reasonable agreement with dates of seismic reflectors based on core data. However, these results showed the postulate that spreading occurred at a steady rate for times of tens of millions of years to be wrong.

Episodic Spreading

On the basis of seismic reflection studies, *Ewing and Ewing* [1967] suggested that the sediment distribution could be explained much more easily in terms of an episodic spreading. A discontinuity in sediment thickness near anomaly 5 (10 m.y. in the *Heirtzler et al.* time scale) was interpreted as indicating an interruption of spreading possibly covering all of Miocene time. *Ewing et al.* [1968*a*] further suggested that the sedimentary structures in the Atlantic basins and the western Pacific implied some important reorganization of spreading, possibly accompanied by a large interruption, most probably at the Mesozoic-Cenozoic boundary. Thus the study of sediment distribution led Ewing et al. to hypothesize three main episodes of drifting: (1) Mesozoic, during which the basins formed; (2) early Cenozoic, during which most of the mid-ocean ridge area was created; and (3) latest Cenozoic, during which the crestal regions appeared. *Langseth et al.* [1966], to explain the distribution of heat-flow values, had also suggested that spreading was episodic.

It should be noted that the ridge-basin and crest-flank boundaries described by Ewing et al. separate three different provinces of magnetic anomalies. Anomaly 5 is the outer limit of a high-amplitude, short-wavelength axial magnetic pattern easily distinguished from the larger-wavelength flank anomalies by a zone of short-amplitude, short-wavelength anomalies [*Heirtzler and Le Pichon*, 1965; *Talwani et al.*, 1965]. This important difference was described by *Vine* [1966] and *Heirtzler et al.* [1968] as perhaps reflecting a change in the average periodicity of reversal of the geomagnetic field and possibly a change of intensity, indicating two different behaviors of the geomagnetic field during early and late Cenozoic time. The outer limit of the magnetic pattern correlated to this day coincides with the ridge-basin boundaries in the Atlantic and the 'opaque layer' boundary in the Pacific, dated by Ewing et al. as latest Mesozoic. We will see later that there are evidences from the magnetic anomalies for major reorganizations in the pattern of spreading at the beginning of each episode. On these bases, we can modify the Heirtzler et al. time scale by giving to anomaly 32 an age of 60 m.y. (early Paleocene) instead of 77 m.y. and by placing an interruption of spreading about 10 m.y. long at anomaly 5, preceded by a general slowing down of the movement. This time scale would not violate any of the core or sediment distribution data. It would also explain the change in magnetic pattern without advocating some over-all change in the average reversal periodicity of the geomagnetic field between early and late Cenozoic times. This adjusted time scale does not disagree with the time scale of Heirtzler et al. by more than 17 m.y.

The objections to the hypothesis of episodic spreading made on the basis of convection current inertia and peak-to-peak correlation of magnetic patterns between oceans are not valid if spreading really corresponds to the response of a thick rigid lithosphere to some underlying stress pattern. In this case, all openings are interrelated and should persist until one or several of them become so poorly adjusted to the stress pattern that a readjustment in the pattern of spreading is necessary. *Ewing et al.* [1968*a*] and *Le Pichon and Heirtzler* [1968] have stressed the fact that such episodic spreading can be more easily correlated with the major orogenies.

On the basis of the magnetic pattern now known, it is possible to reconstruct the earth's surface configuration at the beginning of the two latest major readjustments of spreading—late Miocene (anomaly 5) and early Paleocene (anomalies 31 and 32)—within the assumptions stated in the preceding section. We emphasize that the openings of the oceans are the only movements that can be determined from a study of the magnetic anomaly pattern. Consequently, deformations within continents or possible exchange of land between continents (for example, the Riff zone of Morocco in the Mediterranean region between Africa and Europe) are not considered. In particular, in the case of the Alpine-Himalayan belt, the reconstructions will give the relative movements between the contintal masses as they are now. They are not meant to be detailed paleogeographical maps. Special attention will be paid to the Atlantic and the South Pacific–South Indian oceans, for which the data are easiest to interpret. The problem of the right-angle bend of the magnetic pattern south of the Aleutian trench will not be treated here [*Peter*, 1966]. *Pitman and Hayes* [1968] show that this magnetic pattern can be understood in terms of the migration of the ridge crests toward the east and north, away from the central Pacific. This migration of the crests implies that the main trench system was then along the eastern border (that is, along the west coast of America) and not along the western border (coast of eastern Asia) as it is now.

The World at the Time of Anomaly 5 (Later Miocene)

Figure 7 has been obtained by assuming that Antarctica has not moved during the last 10 m.y. and that the movements of all the other blocks (as defined in Figure 6) were determined by the rotations listed in Table 2. The movement of a continent with respect to Antarctica was determined by estimating (1) the effect of the Pacific-Antarctica rotation, (2) the America-Pacific rotation, and (3) the rotation of Eurasia-America or Africa-America, etc. The total time since anomaly 5 is assumed to have been 10 m.y., so that the finite angle of rotation is 10.8° in the South Pacific, 3.7° in the Atlantic, etc. (see Table 2). To obtain the total movement of any continent with respect to Antarctica, we used the method described in the preceding section. The only difference is that, as we are summing finite rotations and not instantaneous velocities, it is necessary to rotate the centers of rotation before summing the rotations in such a way that they conserve their spatial relations to the blocks being moved. Most of these angles are small, however, and the directions and relative amplitudes of the vectors of differential movement between blocks will be very similar to those shown in Figure 6. For example, the total amount of compression since the end of the Miocene near vector 9 of Figure 6 is about 470 km.

There is no compelling reason to assume that Antarctica has not moved since late Miocene

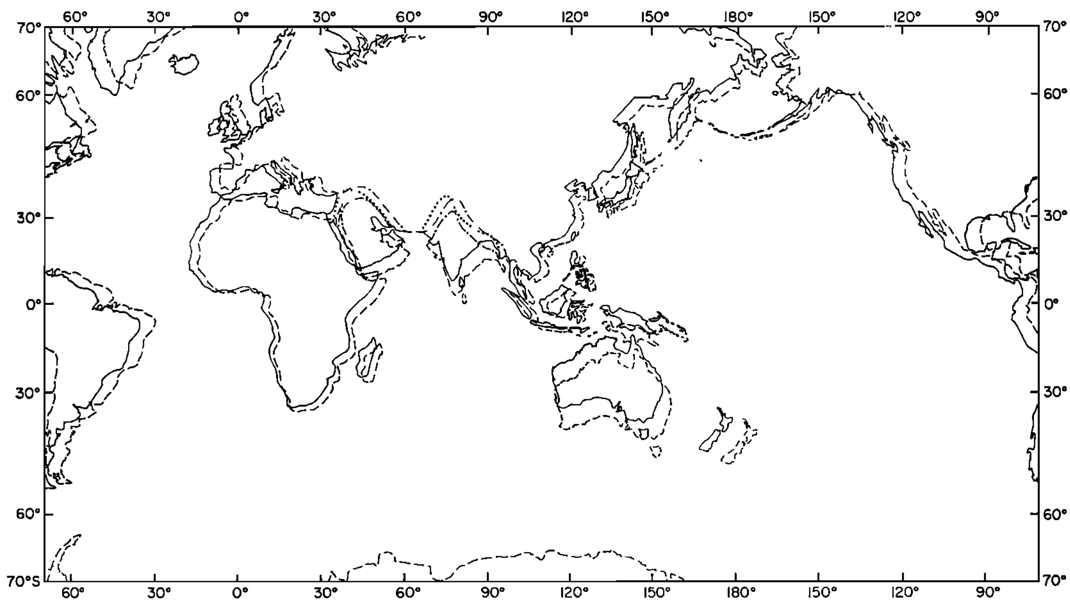

Fig. 7. The positions of the continents at the time of anomaly 5 (≈10 m.y. ago) with respect to Antarctica are shown by dashed lines, the present positions of the continents by full lines. The present northern boundaries of Arabia and India are shown by dotted lines, and the dash-dot lines define the gap which results from the rotations back to 10 m.y. ago.

time. The constant position was assumed for convenience, as we have no way of knowing the absolute movement. However, it is fairly clear that, whichever block is chosen to be fixed, all the others will be displaced at rates of the order of 5 cm/yr (500 km in 10 m.y.). The general movement can be considered to be one of counterclockwise drift relative to Antarctica.

The principal interest of Figure 7 is to complement Figure 6 by showing the general pattern and amplitudes of displacements which have occurred relative to Antarctica in the last 10 m.y. Note in particular the movement of rotation of Africa and the amount of crustal shortening (from 200 to 500 km) which has occurred in the Alpine-Himalayan belt. Note also that no attempt was made to close the Gulf of California in Figure 7. The movement assumed for the computation is somewhat too large ($\approx$500 km) to explain the formation of the Gulf. Because it was difficult to account for the spreading pattern in the North Pacific, which has progressively changed from 10 to 5 m.y. ago, a detailed analysis is not given in this paper.

The World at the Time of Anomaly 31 (Paleocene)

The maximum movement of opening which has occurred since late Miocene time is 10.8°. However, on the basis of the distance between the crests of the ridges and anomaly 31 in each ocean, we can determine that the angles of opening have been as large as 52° in the South Pacific Ocean, 25° in the Atlantic Ocean, etc. (see Table 6). This poses an interesting geometrical problem. As was mentioned earlier, the sum of two finite rotations on a sphere is a rotation, the parameters of which will in general depend on the amplitudes of the finite angles of rotation. If we consider the Indian Ocean, for example, the sum of the rotation of the Indian block away from Africa and of the rotation of the Africa block away from Antarctica will be a rotation of the Indian block away from Antarctica, the parameters of which will progressively change with time as the two other openings progress. This means that the trends of the transform faults and the amplitudes of the spreading rates will change with time, if the two other rotations keep constant parameters.

Of course, there is no way of knowing which of the three rotations will adjust itself with time to the two others. It is even conceivable that all three rotations will progressively adjust to each other with time. Also, it is possible that, instead of a gradual modification of the parameters of rotation, there is a discontinuous change of the parameters when the stresses produced by the deformation have reached a certain level. This might eventually lead to the 'death' of a ridge and the 'birth' of a new one along completely new lines. The great complexity of the Indian Ocean, and perhaps also of the Norwegian Sea–Arctic Ocean region, is probably caused by these facts. One can consider that the role of these two oceans is to resolve the geometrical problems caused by the progressive openings of the Atlantic and Pacific oceans. This problem, of course, introduces great complexity and considerable uncertainty in the attempt to reconstruct the world in the distant past because the set of parameters given by the present magnetic coverage of the oceans is incomplete and inaccurate.

We do not know the movement of America relative to the Pacific block before the time of anomaly 5, as there was presumably a trench system along the west coast of North America. Consequently, we cannot follow the paths used in the preceding section to obtain the relative movement of any continent with respect to Antarctica. We can instead obtain separately the movements of Australia and New Zealand with respect to Antarctica and of all the other continents with respect to Africa. Africa and Antarctica are then assumed to have remained in their present positions throughout Cenozoic time. This leads us to make two assumptions. The first and most impotant one will be that the movement of Africa relative to Antarctica has on the average been small since Paleocene time. This is supported by the paleomagnetic data [see, for example, *Gough et al.*, 1964], magnetic data (i.e., the absence of clear magnetic pattern [*Le Pichon and Heirtzler*, 1968]), and sediment data (i.e., the large sediment cover of the ridge flanks up to the crestal zone, M. Ewing, personal communication). With this approximation, we do not need to know the movement of America with respect to the Pacific block. The second assumption involves the choice of an average center of rotation of Australia with respect to Antarctica. This center of rotation should satisfy the probable trends of the fracture zones south of Australia. It should also satisfy the progressive increase in the distance between anomaly 13 and the ridge crest from west to east in the southwest mid-Indian Ocean ridge [*Le Pichon and Heirtzler*, 1968]. The center of rotation obtained (36°S, 53°E) may be in error by as much as 10°. However, an error of even this magnitude will not seriously alter the results. The angles of rotation chosen (Table 6) are such that they bring into coincidence the two anomaly 31 lines on each side of the crest (when only one is known, we assume that the other is symmetric with respect to the crest). In the Indian Ocean no anomalies older than anomaly 18 have been identified. Anomaly 18 is at the base of the Australian continental rise (see Figure 4). Before the time of anomaly 18, Australia and Antarctica must have formed a single continent. On the other hand, anomaly 18 is not positively identified over the Carlsberg ridge. Over the ridge southeast of Mauritius no anomalies were identified beyond anomaly 18, and there are indications that a major readjustment in the pattern of spreading occurred at this time. Consequently, in Figures 8 and 10, India was rotated by the amount necessary to superpose the two anomaly 18 lines south of Mauritius, the movement before the time of anomaly 18 being unknown. Finally, the Arctic opening was assumed to have started 60 m.y. ago, on the basis of the Paleocene-Eocene basalt eruptions presumably indicative of the initial breakup (see, for example, *Vine* [1966]). Table 6 summarizes the rotations used to obtain Figure 8.

Figure 8 is the reconstruction of the world in Paleocene time obtained by resorbing the amount of earth's surface created by sea-floor spreading at the axes of the mid-ocean ridges after the time of anomaly 31. The exact position of the Australia–New Zealand–Antarctica block with respect to the rest of the continents is not known. In regions of Tertiary mountain belts the surface of the crust was presumably much larger before folding than after. A large part of the gaps appearing in these regions (e.g., between India-Arabia and Eurasia, and possibly also between Europe and Africa) may have been occupied by continental crust. Eurasia was treated as a unit, and the differential movement between eastern Asia and North America implies that the Pacific Ocean was larger than it is now. If, instead, eastern Asia and North America are assumed to have moved as a unit, a large gap would have existed between eastern Asia and the remaining part of Eurasia along what is now the Verkhoyansk Mountains. It is quite possible that the opening of the Labrador Sea is an early Cenozoic phenomenon, in which case the whole Eurasia-Greenland block should be moved toward the west with respect to Africa in Figure 8.

In spite of the many limitations which apply to this reconstruction, its main features are a necessary consequence of the magnetic anomaly pattern described by *Heirtzler et al.* [1968]. By Paleocene time, the present South Pacific Ocean did not exist and the present North and equatorial Pacific were larger. Either a large 'Tethys' sea existed or a minimum amount of crustal shortening, ranging from 500 km in the west to 1000 km north of India, must have occurred since. This may have been accompanied in early Cenozoic time by very large shearing between

TABLE 6. Relative Rotations Used for Figures 8, 9, and 10*

	Latitude	Longitude	Angle of Rotation
New Zealand-Antarctica	70N	62W	+52° (anomaly 31), +21° (anomaly 18)
America-Africa	58N	37W	+25° (anomaly 31)
Eurasia-America†	78N	102E	−17° (to resorb Reikjanes ridge)
Australia-Antarctica	36S	53E	−31° (anomaly 18)‡
Arabia-Africa	26N	21E	−7° (to close Gulf of Aden)
India-Africa	26N	21E	−17° (anomaly 18)§

* Antarctica and Africa fixed in their present positions.
† America in its present position.
‡ Anomaly 18 is at the foot of the Australian continental rise: there are no older anomalies.
§ No anomalies older than anomaly 18 were identified.

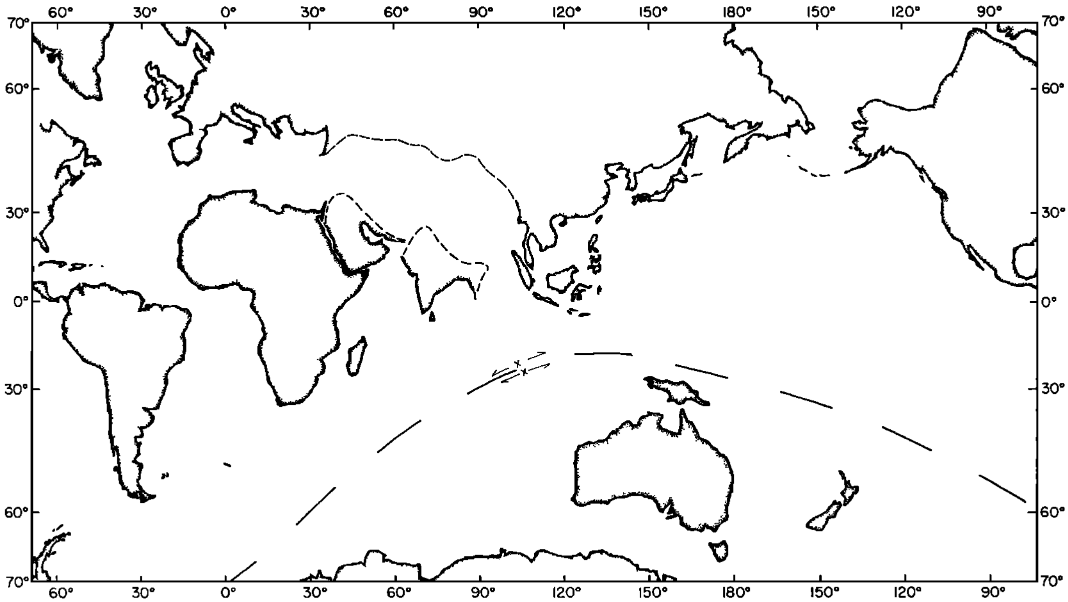

Fig. 8. The positions of the continents at the time of anomaly 31 (Paleocene). The dashed line indicates that the relative positions of the two groups of continents on each side of it were not known: Antarctica and Africa are assumed to have been in their present positions. See text and Table 7 for details.

the north and south shores of the Tethys if the Labrador sea opened as late as Paleocene time.

The Atlantic Opening

To illustrate in more detail the implications of this reconstruction, we show in larger scale (Figure 9) the reconstruction of the Atlantic Ocean in Paleocene time. The tracings of the present-day isobaths in the basins help us to visualize the changes resulting from this opening during Cenozoic time. A first conclusion obtained by an examination of Figure 9 is that the effect of applying the rotation determined by the distance to anomaly 31 in the South Atlantic has been to resorb the present mid-Atlantic ridge area in the North Atlantic as well as in the South Atlantic. In Figure 9 the ocean basins, as we know them, still have their present extent. This observation supports the hypothesis that the present mid-Atlantic ridge, in the North Atlantic as well as in the South Atlantic, was created by spreading during the Cenozoic era, whereas the basins are pre-Cenozoic structures. Consequently, anomaly 31 should be found at the boundary ridge-basins in the North Atlantic. In fact, according to this hypothesis, we can predict the location of any magnetic anomaly over the whole mid-Atlantic ridge and south of the Azores-Gibraltar ridge.

The Mesozoic fracture zones. Figure 9 was obtained by rotating North and South America as a unit by 25° around 58°N, 37°W. *Bullard et al.* [1965] have given the rotations necessary to bring North America and South America into best fit with Africa. If we substract the Cenozoic rotation from the Bullard et al. rotations, the residual rotations obtained describe the movements involved in the pre-Cenozoic drift, provided that they occurred during one single episode of spreading. If, on the other hand, the pre-Cenozoic drifts occurred during two or more episodes of spreading, the movements of North and South America would probably be described by two or more successive rotations each. This idea can be tested by comparing the lines of flow corresponding to a single pre-Cenozoic rotation with the trends of the major fracture zones in the basins.

The residual rotations obtained by subtracting the Cenozoic rotation from the Bullard et al. rotations are listed in Table 7. These residual rotations have been used to draw lines of flow (Figure 9) which should be compared with the trends of major features in the basins. As noted

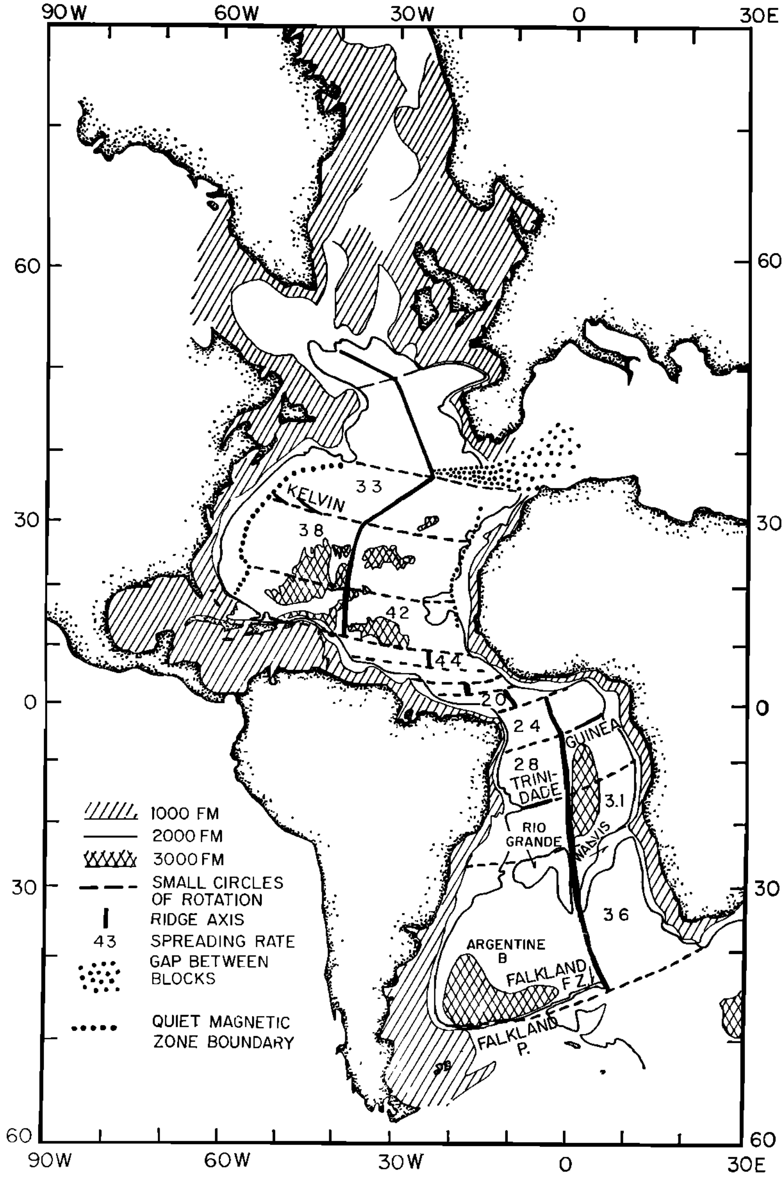

Fig. 9. The Atlantic at the time of anomaly 31. The possible locations of major Mesozoic fracture zones, shown by dashed lines, were obtained by assuming that the pre-Cenozoic drifts can be described for South and North America by a single rotation each. The average spreading rate in centimeters per year for each block is obtained by assuming a constant rate of spreading between 120 and 70 m.y. ago. The bathymetry is not shown for the Caribbean and Gulf of Mexico. Notice that the trends of the Falkland plateau and fracture zone, Rio Grande and Walvis ridges, Trinidade ridge, Guinea ridge, and Kelvin seamount chain agree well with the predicted trends. See text and Table 7 for details.

by Morgan, the lines of flow defined by these rotations do not agree with the lines of flow of the Cenozoic rotations. A major change in the pattern of spreading must have occurred in the Atlantic between the Mesozoic and Cenozoic eras.

The northern boundary of the Falkland plateau and its eastern extension, the Falkland

TABLE 7. Rotations Used for Figure 9*

	Pole of Rotation		
	Latitude	Longitude	Angle of Rotation
Bullard et al. [1965] Rotations			
North America-Africa	67.6N	14.0W	+74.8°
South America-Africa	44.1N	30.3W	+56.1°
Rotation for Anomaly 31			
America-Africa	58N	37W	+25°
Residual Rotations for Time before Anomaly 31			
North America-Africa	73.9N	4.8W	+50.8°† or 42.0°‡
South America-Africa	35.4N	21.0W	+32.5°

* Africa in its present position.
† Fit to 500-fathom line.
‡ Fit to 'quiet magnetic zone' boundary.

fracture zone, nearly follows the line of flow predicted for the tip of South Africa. No clear break in the trend of this fault zone can be detected. *Le Pichon et al.* [1968] have described this topographic feature as a steep scarp 2 to 3 km high which extends for more than 2000 km. They have shown in particular that the Falkland fracture zone ends abruptly to the east near 28°W, the location of anomaly 31. The ending of the Falkland fracture zone at the boundary of the Cenozoic mid-Atlantic ridge is another confirmation that the Cenozoic episode of spreading was not a simple continuation of the Mesozoic episode of spreading.

Wilson [1965*b*] had noted that the terminations of the Walvis and Rio Grande ridges correspond to two conjugate points in the fit of South America to Africa. Figure 9 shows that the northern boundaries of the Walvis and Rio Grande ridges follow the same flow line. *Le Pichon et al.* [1966] have described the northern boundary of the Rio Grande rise as a large continuous fault scarp trending nearly east-west, with numerous outcrops of upper Mesozoic and Cenozoic sediments. Like the Falkland plateau scarp, the northern scarps of the Walvis and Rio Grande ridges mark the locations of former Mesozoic fracture zones. The subsequent history of these features was controlled by these structural trends.

Figure 9 shows that, similarly, the ridge connecting the island of Trinidade to the Brazilian continental rise, the Guinea ridge, and the Kelvin seamount chain closely follow the trends predicted by the flow lines. Accordingly, a fracture zone should extend along the trend followed by the southeast Newfoundland ridge, marking the upper limit of the drift of North America. This evidence suggests that the pre-Cenozoic drift in the Atlantic was produced during a single episode of spreading, presumably during late Mesozoic time. If there was an early breakup of the continents during Permian time, as suggested by *McElhinny* [1968], the movements involved must have been very limited or must have occurred along exactly the same flow lines.

The 'quiet' magnetic zones. A complication is introduced by the existence of the band of 'quiet' magnetic anomaly field paralleling the northeast American shelf [*Heirtzler and Hayes*, 1967]. A similar but much narrower zone exists along the west coast of North Africa within the 2000-fathom isobath. Heirtzler and Hayes attribute the quiet zones to spreading during the long period of the Permian without reversals of the geomagnetic field. They could be portions of continental margins which subsided to their present depths when the active spreading started, in Aptian-Albian time. The history of subsidence of the adjacent continental margin is well known, and the base of the Lower Cretaceous (from drilling data) is now found at depths equivalent to the adjacent oceanic depths in parts of the Florida platform and Bahama banks [*Sheridan et al.*, 1966].

Support for this hypothesis comes from cores raised from 5 km water depth from the Lower Cretaceous (Barremian to Albian) seismic reflector β, which is just above horizon B in the sedimentary column [*Ewing et al.*, 1966]. According to T. Saito (personal communication), these cores indicate a shallow-water environment. *Houtz et al.* [1968] report that this reflector is marked by a large increase in sediment compressional velocity and can be recognized, on this basis, at several locations near the continental margin. *Heezen and Sheridan* [1966] reported the dredging of shallow-water Lower Cretaceous (Neocomian) rocks at a depth of 5 km on the Blake plateau scarp. They interpreted it as indicating rapid subsidence during earliest Cretaceous time. This hypothesis would necessitate a conversion from continental crust to oceanic crust by a process similar to the one presumably responsible for the subsidence of the

Gulf of Mexico (according to the interpretation given by *Ewing et al.* [1962] of the diapirs as salt domes). One possible process may be the subcrustal erosion advocated by *Van Bemmelen* [1966]. If this hypothesis is accepted, the fit between Africa and North America should be made along these magnetic boundaries as has been done by *Drake and Nafe* [1967].

Mesozoic spreading rates: The Caribbean. If we assume that the active Mesozoic drifts of North and South America occurred simultaneously and at a steady rate, starting 120 m.y. ago and ending 70 m.y. ago, it is possible to compute the corresponding spreading rate at any location along the axis of the ridge. In Figure 9 the average Mesozoic spreading rate within each block between pairs of fracture zones is given in centimeters per year (the total movement of drift is equal to twice this number). Note the change in spreading rate by more than a factor of 2 in the equatorial region. The divergence of the flow lines in this boundary region between North and South American drifts resulted in the creation of the Caribbean, presumably by subsidiary spreading. The general direction of Mesozoic spreading in the Caribbean is perpendicular to the trend of the Beata ridge.

Most of the Mesozoic drift probably occurred in Early and Middle Cretaceous times, and by the Late Cretaceous the movement was coming to a stop, as western North America was progressively overriding the adjacent trench system [*Hamilton and Myers*, 1966]. Thus the actual spreading rates may have been as high as 6 to 8 cm/yr during the Early Cretaceous and much smaller during the Late Cretaceous.

Europe and Greeland movements: The Azores-Gibraltar ridge. At the time Figure 9 was drawn, we accepted *Vine*'s[1966] assumption that the breakup between Greenland and Great Britain started 60 m.y. ago at the time of the Paleocene-Eocene basalt eruption. The Labrador mid-ocean ridge being now a 'dead' ridge, we assumed that it corresponded to an earlier breakup. Consequently, in Figure 9 the Labrador Sea has its present extent, whereas the Reikjanes ridge area is closed. This results in the creation of a gap southwest of Spain, which indicates the amount of compression that should have occurred in the region during Cenozoic time along what is now the Azores-Gibraltar ridge. Thus, in this reconstruction, Spain and Africa may have been in contact all the time.

Mayhew and Drake [1968] have identified the magnetic pattern over the Labrador Sea and over the basin west of the Reikjanes ridge. Their results confirm the fact that the rift between Greenland and Eurasia started near anomaly 31 (60 m.y. ago). However, they indicate, apparently, that the Labrador Sea was produced by spreading during the interval of time corresponding to anomalies 31–27, that is, during Paleocene time. If this is so, the Labrador Sea should be closed in Figure 9, and Spain should be separated from Europe by as much as 1500 km. The movement during the Cenozoic thus should have resulted mostly in strong shear during the Paleocene, then mostly in compression from the Eocene to the recent between Eurasia and Africa.

The general paleogeography of the Atlantic Ocean at the end of the Mesozoic era was such that the deep-water circulation must have been very limited. The northern source of North Atlantic deep water did not exist, as the Labrador Sea was closed. The deep-sea communications between North and South Atlantic were probably closed by the mid-ocean ridge at the equator. Finally, the Falkland fracture zone was closing the southwest Atlantic to circulation of deep water coming from the south. The present deep-sea circulation must have established itself at the beginning of the Cenozoic episode of spreading [*Ewing et al.*, 1968*b*].

Asymmetry of the ridge in the South Atlantic. The location of anomaly 31 in the South Atlantic is such that the ridge is not median. The western basins are much wider than the eastern basins. Yet all the observations made to this day indicate that spreading occurs at nearly equal rates on each side of the crest of the mid-ocean ridges. If spreading is supposed to have occurred symmetrically with respect to the crest of the ridge, the western two-thirds of the Argentine basin should represent older crust produced in earlier spreading. As no change in the direction of flow is indicated by the trend of the Falkland plateau scarp, it is probable that an eastward shift in the position of the crest occurred at the beginning of Mesozoic time, during the same episode of spreading. This probable evolution is shown in Figure 10, where the main phases of Meso-

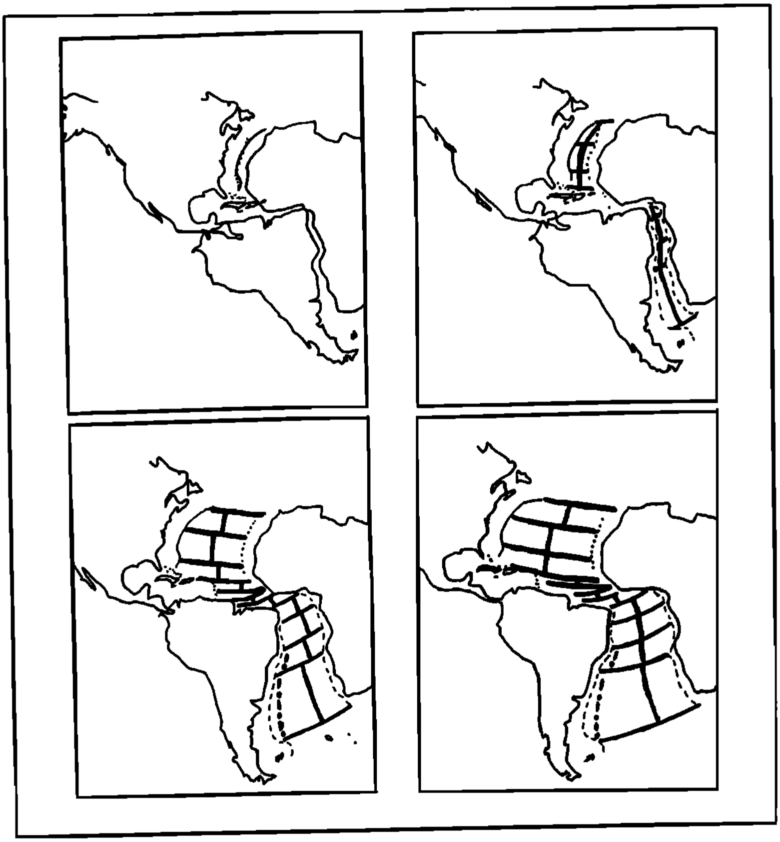

Fig. 10. The Mesozoic episode of spreading in the Atlantic. These reconstructions were obtained by assuming that North and South America parted simultaneously from Africa 120 m.y. ago (upper left) and reached the position corresponding to anomaly 31 (Figure 9) about 90 m.y. ago (lower right) after a single movement of rotation for each. The asymmetry of the ridge crest in the South Atlantic at the time of anomaly 31 is explained by a shift in the ridge crest positions in the Early Cretaceous. The fit is made to the 'quiet' magnetic zone boundaries in the North Atlantic and to the 500-fathom line in the South Atlantic [*Bullard et al.*, 1965]. See Table 7. The active ridge crests and fracture zones are represented by a thick continuous line, the abandoned ridge crest by a thick dash-dot line.

zoic drift have been reconstructed using the rotations listed in Table 7. The great thickness of Mesozoic sediments in the Argentine basin [*Ewing et al.*, 1968*b*] may be explained in this way, as the sedimentation rates must have been much larger when the ocean was still very narrow.

History of the opening. The following still very tentative history of the opening of the Atlantic Ocean, which is in agreement with some of the conclusions of *Dickson et al.* [1968] for the South Atlantic, is outlined:

1. The active phase of drift began in Aptian-Albian time, about 120 m.y. ago [*King*, 1962; *Wilson*, 1965*b*]. The North Atlantic 'quiet' magnetic zones in the continent are included with the original continent of *Bullard et al.* [1965]. The initiation of drift was accompanied by the subsidence of a large part of the northeast American continental margin, possibly related to the earlier (Jurassic) Gulf of Mexico subsidence. *McElhinny* [1968] has presented paleomagnetic evidence for some opening of the South Atlantic since Permian time. Although there is no evidence for considering parts of the South Atlantic basins to be 100 m.y. older than the others, it is probable that early rifting and subsidence began to appear along the line of parting in both the

North and South Atlantic in Jurassic time. This may have resulted in the creation of marine gulfs of limited width, long before the episode of fast spreading began in the Early Cretaceous. For example, the first signs of uplift in the Red Sea–Gulf of Aden region appeared at least 50 m.y. ago. Yet most of their deeps were probably created after late Miocene time (10 m.y. ago). This early rifting could explain the few examples of deposition of marine sediments during the Late Jurassic [e.g., *Colom,* 1955].

2. A fast episode of spreading, possibly 30 m.y. long, followed. Figure 10 shows the probable evolution of this episode of drift. Notice that after the first 10 m.y. of drift the crest of the ridge in the South Atlantic must have migrated to a more easterly position to reach the nonmedian line along which it was lying at the end of the Mesozoic era. The original positions of the continents at the end of Jurassic and beginning of Cretaceous time were obtained by using the Bullard et al. fit for South America and making the fit of North America along the boundary of the 'quiet' magnetic zone [*Drake and Nafe,* 1967]. Notice that some distortion is implied in the Caribbean, as Puerto Rico overlaps Africa. Also the southern tip of Central America overlaps South America. However, a great part of this overlap corresponds to Cretaceous or more recent geological formations [*Edgar,* 1968].

It is probable that by Middle Cretaceous time the fast episode of drift was ending. The Caribbean had then essentially its present extent. Great fracture zones were occupying the positions of the northern boundaries of the Walvis and Rio Grande ridges and of the Falkland plateau. The Guinea ridge, Trinidade ridge, Kelvin seamount group, and southeast Newfoundland ridge were probably fracture zones too. As North America and Eurasia moved as a unit, a large extensional shear zone was created between Africa and Eurasia.

During this period the deep-water circulation was of the closed-basin type, and the sedimentation rates, especially in the early stages of breakup, must have been very large, as the ratio of coast periphery to area of sea was much larger than now. By Late Cretaceous time, the spreading must have already slowed down considerably, coming progressively to a complete stop. This may have been due to resistance encountered in the overriding of the adjacent trench system by the western border of America [*Hamilton and Myers,* 1966]. The deposition of horizon A [*Ewing et al.,* 1966] seems to be related to the end of this episode of spreading. Perhaps the flow of turbidites was triggered by the regression associated with the subsidence of the Mesozoic mid-ocean ridges [*Menard,* 1964, p. 238].

3. By Paleocene time, the movement of opening resumed, following a new pattern of flow. North and South America were moving as a unit at this time, except possibly for some small differential movement. The actively spreading ridge extended north to the Labrador Sea and the Norwegian and Arctic seas, according to the identification of magnetic anomalies by Mayhew and Drake. The southeastward movement of Eurasia relative to Africa must have created a zone of shear between Eurasia and Africa. This inversion of tectonic forces, from extensional shear in Mesozoic time to shear and their compression in Cenozoic, is a necessary consequence of the interpretation of the magnetic anomalies in the Labrador Sea and Reikjanes ridge area. It might explain the complexity of the phenomenon named by *Van Hilten and Zijderveld* [1966] the 'Tethys Twist.' By Eocene time, the Labrador Sea was opened and the mid-Labrador Sea ridge had died.

By Oligocene time, the spreading rate had begun to slow down, and it came to a complete stop in the Miocene. This is the time during which northwest America probably overrode first the trench system and then the ridge crest situated along its border [*Vine,* 1966]. It seems that the terminations of both Mesozoic and early Cenozoic episodes of spreading coincide with the times at which western America overrode the adjacent trench system. The episodes may have been terminated because the lithosphere, which was sinking along the trench [*Oliver and Isacks,* 1967], had sunk to the maximum depth it could reach. These episodes of spreading also correlate well with the compressive period which culminated in the Oligocene and Miocene in the Mediterranean [*Glangeaud,* 1961], when North Africa and Europe came into close contact. The block faulting on the northern mid-Atlantic ridge and the renewed uplift of the Walvis and Rio Grande ridges [*Ewing et al.*, 1966] and possibly of the Falkland plateau along old fracture zones lines may be related to this stoppage of spreading. *Le Pichon et al.* [1966] have reported the recovery of lower Eocene turbidites from the summit of the Rio Grande rise, now at 800 m depth. The beginning of the early Cenozoic episode of spreading opened the Atlantic basin to deep-water circulation and started a change in the pattern of sedimentation [*Ewing et al.*, 1968].

4. In late Miocene time, the third cycle of spreading started apparently along the same pattern of flow as the previous one in the Atlantic, but at a slower rate, and produced the crestal region devoid of sediments [*Ewing and Ewing*, 1967]. In the North Pacific, however, a new pattern of spreading had established itself, in which the Pacific Ocean floor was now rotating away from North America instead of being thrust below it along a trench system.

This reconstruction does not explain why the part of the mid-Atlantic ridge situated north of the line formed by the northern boundaries of the Walvis and Rio Grande ridges is so much more fractured and devoid of sediments than the part immediately south of it [*Ewing et al.*, 1966]. The hypothesis of Ewing et al. of a large Miocene tectonic disturbance which disrupted the crust north of this boundary at the end of the early Cenozoic cycle of spreading still seems to be the only one available. The reason for this drastic change on each side of the boundary is not clear, but there is little doubt that it has been and still is an important structural division in the South Atlantic.

The South Pacific and Indian Ocean Openings

Figure 11 shows in greater detail the evolution of the South Pacific and Indian oceans since Paleocene time. The value of this reconstruction can be judged from how well the anomaly lines, shown previously in Figures 2 and 4, fit together. The positions of the New Zealand plateau and of the South Pacific ridge crest are shown at two different times: anomaly 31 (Paleocene) and anomaly 18 (late Eocene). As Antarctica is assumed to be fixed, the ridge crest was migrating away from it at half the speed of the New Zealand plateau. The positions of Australia relative to Antarctica and of India relative to Africa are plotted for the time of anomaly 18 (late Eocene). As mentioned previously, the position of India before the time of anomaly 18 is unknown. Eurasia is shown in the same position as in Figures 8 and 9 (i.e., at the time of anomaly 31, the Labrador Sea having already opened). The dashed lines represent the lines of flow of Australia and of the New Zealand plateau during the Cenozoic.

The Indian Ocean. The evolution of the Indian Ocean during the Cenozoic is still incompletely understood, and the tentative conclusions of *Le Pichon and Heirtzler* [1968] will be summarized here. Before early Eocene time, the movement of India had to be due north, corresponding to a rotation around a point in central Africa (see Figure 11). This movement probably resulted from spreading along an east-west ridge in the then much greater basin north of Broken ridge. Broken ridge is probably continental in origin. Eurasia, in late Eocene time, would have been a few hundred kilometers south of the position it occupies in Figure 11. Consequently, the present northern border of India was then within 1000 km of the present border of Eurasia. As this was the time of the first large orogenic phase, a total compression of the order of 1000 km must be assumed for this area since Eocene time.

In any case, the pattern of spreading in the Indian Ocean readjusted itself at the time of anomaly 18, when a northwest-southeast axis became active for the first time, from the then closed Red Sea and Gulf of Aden to Australia. In the beginning there must have been considerable differential motion along the Ninetyest ridge, which probably came into evidence as a result of the motion. Some differential motion probably also occurred along the southwest branch of the ridge to reconcile the direction of spreading south of Australia with the direction of spreading on the Carlsberg ridge. By Miocene time the spreading had completely stopped, at the time of the peak phase of the Himalayan orogeny. It resumed at the time of anomaly 5 (latest Miocene), creating the Red Sea and Aden axial troughs in particular.

Australia and New Zealand. The evolution of the northern and central Indian Ocean is difficult to obtain from a study of the magnetic pattern. It is much easier to decipher the

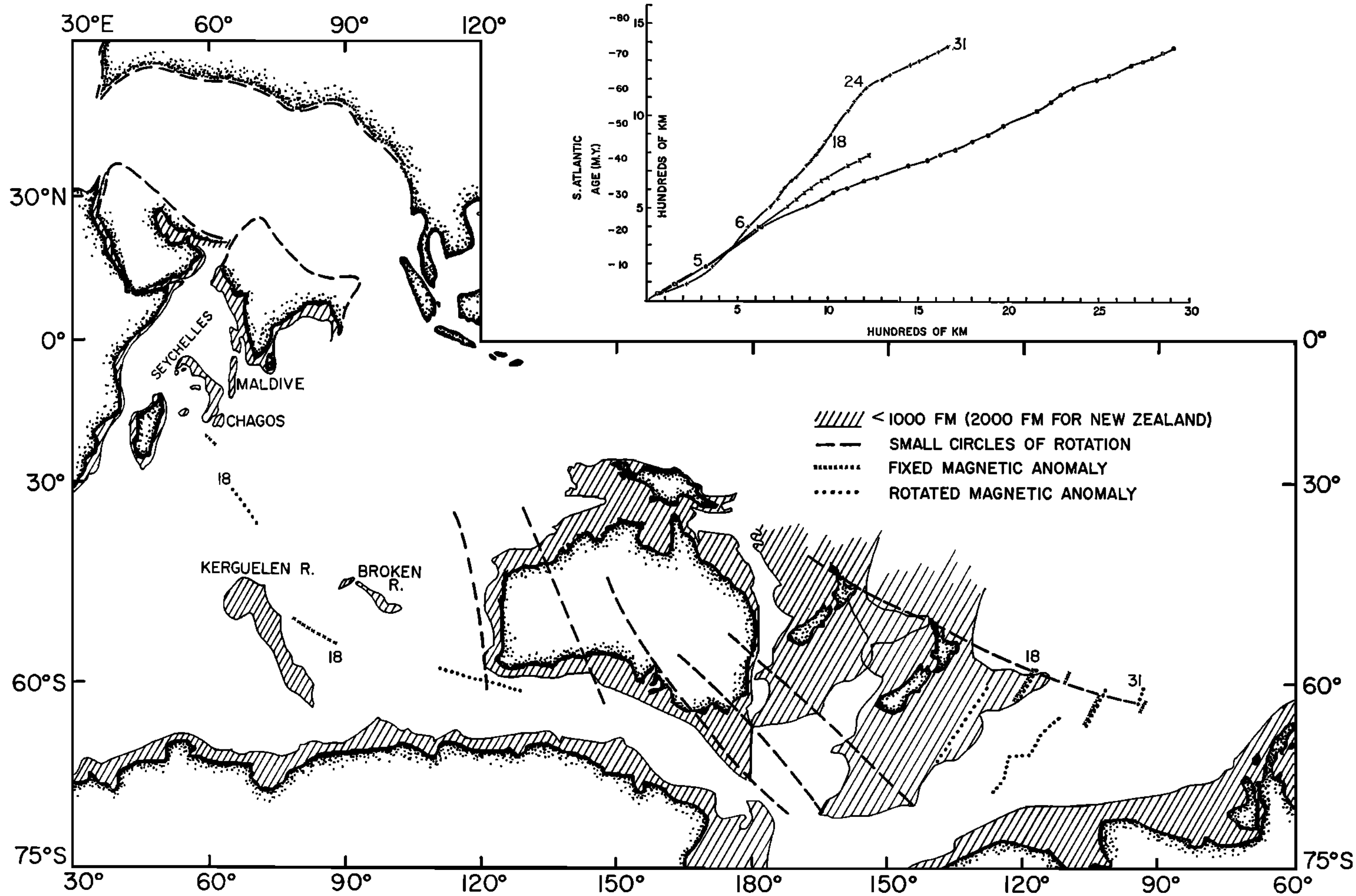

Fig. 11. The Indian and South Pacific oceans at the times of anomalies 31 (Paleocene) and 18 (late Eocene). See text and Table 7 for explanations. The curves of distance of a magnetic anomaly from the crest in a given ocean versus distance of the same anomaly from the crest in the Atlantic Ocean are, respectively, from left to right for the South Pacific, South Indian, and North Pacific oceans [from *Heirtzler et al.*, 1968].

history of spreading in the South Pacific and South Indian oceans. We see in Figure 11 that the New Zealand plateau separated from Antarctica in Paleocene time at a relatively fast spreading rate (see inset, Figure 11). By the time of anomaly 24 (early Eocene), the spreading rate slowed by a factor of 3, as the New Zealand plateau was approaching eastern Australia. By the time of anomaly 18 (late Eocene), Australia began to detach itself from Antarctica, along flow lines parallel to those of the New Zealand plateau. Australia was then moving twice as fast as New Zealand. Consequently, during the period of extension between Australia and New Zealand the present Tasman Sea was created. When the spreading resumed, after the Miocene interruption, the velocity of spreading became greater in the South Pacific than in the South Indian Ocean, resulting in general compression between New Zealand and Australia. Thus, on the basis of the magnetic anomaly pattern, we can infer a very complex history for New Zealand during the Cenozoic, a period of compression in Paleocene and Eocene times, a period of extension in Oligocene and early Miocene times, and a period of compression again in the Pliocene. Furthermore, according to this reconstruction, Australia and the New Zealand plateau were probably in contact in late Eocene time.

IV. Conclusions

Morgan [1968] has suggested that the surface of the earth can be approximated by a small number of rigid blocks in relative motion with respect to each other. This assumption has been confirmed by a geometrical analysis of the data on sea-floor spreading. In accordance with this concept, we have given a simplified but complete and consistent picture of the global pattern of surface motion. We have shown that all movements are interrelated, so that no spreading mid-ocean ridge can be understood independently of the others. Thus any major change in the pattern of spreading must be global.

The results support *Elsasser* [1968], *McKenzie* [1967], *Morgan* [1968], and *Oliver and Isacks'* [1967] model of a rigid and mobile lithosphere (tectosphere) several tens of kilometers thick on top of a weak asthenosphere. The mechanism of sea-floor spreading at the mid-ocean ridges, then, corresponds to the breaking apart of a plate, preferably along lines of weakness, in response to a stress pattern.

We have attempted to apply this concept to obtain a reconstruction of the history of spreading during Cenozoic time. Three main episodes of spreading are recognized—late Mesozoic, early Cenozoic, and late Cenozoic. The beginning of each cycle of spreading is marked by the reorganization of the global pattern of motion. A correlation is made between slowing of spreading at the ends of the two previous cycles and paroxysms of orogenic phases. This history of spreading follows closely one advocated by *Ewing et al.* [1968] to explain the sediment distribution.

The results presented by Oliver and Isacks suggest a possible mechanism to account for the episodicity of sea-floor spreading. The main zones along which the lithosphere is sinking are the deep-sea trenches. Because of thermal inertia, the lithosphere apparently maintains its identity to a depth as great as 700 km. Let us assume that there is a part of the mantle, possibly below 800 km, into which the lithosphere cannot penetrate further. At first, the adjacent continental block will probably be forced to override the island arc and trench system. Then the spreading will have to stop until a new trench system has been formed. As the rate of thrusting of the oceanic crust along the trenches is of the order of 6 cm/yr, the average length of the active part of a cycle of spreading is unlikely to exceed 30 m.y., corresponding to 1800 km of crust. This length roughly corresponds to the length of a Gutenberg fault zone having a dip of 30° and extending to a depth of 800 km.

Finally, in this paper, regions in which earth's surface is shortened or destroyed are called regions of compression. Most geologists would agree that the Alpine-Himalayan belt is indeed a region of compression. It has been argued convincingly, however, that deep-sea trenches are regions of tensile stress [e.g., *Worzel*, 1965]. *Elsasser* [1968] has suggested that the tectosphere becomes denser as it slides down the Gutenberg fault zone and acquires a sufficiently greater density than surrounding mantle material to sink on its own. 'The motion . . . then leads to a tensile pull in the adjacent part of the tectosphere.' Consider the India-Pacific boundary, for example. From Macquarie Island to the Kermadec trench the differential movement of compression between the two plates results in compressional surface features, but along the Kermadec and Tonga trenches, where the differential movement is larger, the Pacific tectosphere has decoupled itself from the adjacent block and sinks on its own, creating the surface tensional features associated with the trenches.

As the differential movement of compression between two blocks increases, the associated surface compressional features apparently become larger and reach a maximum for a rate of movement of about 5–6 cm/yr (Himalayas). At larger rates, the lithosphere sinks along an active trench, and the associated surface features are tensional instead of compressional. The narrow range of rates of differential movement associated with the trenches where active thrusting of the tectosphere occurs (6–9 cm/yr) may be one of the significant results of this study.

Appendix

Determination of center of rotation from azimuths of fracture zones. We assume that the latitude Lat_i, longitude $Long_i$, and azimuth Azi_i of the fracture zones at N points along the crest of the ridge are known.

1. Start with an estimated position of the center of rotation (latitude *Plat* and longitude *Plong*).

2. Compute the theoretical azimuth $Tazi_i$ at the N points. $Tazi_i$ is the azimuth of the tangent to the small circle having for center *Plat* and *Plong* and passing by Lat_i and $Long_i$.

3. Compute the sum of the squares of the deviations

$$Sum = \sum_{i=1}^{N} (Azi_i - Tazi_i)^2$$

4. Modify *Plat* and *Plong* until *Sum* is minimum.

The actual search is made through a grid centered on the original *Plat* and *Plong*. The process is repeated until the point is located to better than 1°. The convergence of the computation can be estimated from the sizes of the ellipses in Figure 1.

Determination of center of rotation from spreading rates. Let R be the spreading rate measured along a perpendicular to the crest of the ridge having the azimuth *Azi*. Let *Spr* be the true spreading rate measured along a tangent to the small circle (centered on the center of rotation) which has the azimuth *Tazi*. Let *Rmax* be the maximum true spreading rate (along the equator of rotation) and $Sprn = Spr/Rmax$ be the normalized true spreading rate.

Then *Sprn* is equal to the sine of the distance (in degrees of arc) from the center of rotation and $Sprn = R/[Rmax \cdot \cos(Azi - Tazi)]$

We assume that the latitude Lat_i, longitude $Long_i$, and spreading rate R_i (measured along a perpendicular to the crest having the azimuth Azi_i) at N points along the crest of the ridge are known.

1. Start with an estimated position of the center of rotation (*Plat, Plong*) and an estimated maximum true spreading rate *Rmax*.

2. Compute $Sprn_i$ and $Tazi_i$ at the N points.

3. Compute the sum of the squares of the deviations

$$Sum = \sum_{i=1}^{N} \{[R_i/(Rmax \cos(Azi_i - Tazi_i)] - Sprn_i)\}^2$$

4. Modify *Plat* and *Plong* until *Sum* is minimum.

5. When the location is obtained to better than 1°, the process is resumed with a different value of *Rmax*.

The method is very sensitive to the value of *Rmax*. It is not very sensitive to the difference between true spreading rate and spreading rate measured along a perpendicular to the crest (the latter varies as the inverse of the cosine of the difference in azimuths).

For example, for the South Pacific, for $Rmax = 6.3$ cm/yr, $Plat = 70.9°$S, $Plong = 127.1°$E, and the standard deviation *SD* is 0.059. For $Rmax = 5.7$ cm/yr, $Plat = 66.3°$S, $Plong = 118.7°$E, and $SD = 0.065$. The minimum $SD = 0.058$ is found for $Rmax = 6.0$, $Plat = 68.3°$S, and $Plong = 123.3°$E.

For the Atlantic Ocean, for $Rmax = 2.25$ cm/yr, $Plat = 69.6°N$, $Plong = 54.7°W$, and $SD = 0.082$. For Rmax $= 1.85$, $Plat = 64.4°N$, $Plong = 10.5°W$, and $SD = 0.096$. And the minimum $SD = 0.065$ is found for $Rmax = 2.05$, $Plat = 68.6°N$, and $Plong = 31.8°W$.

The location is poorly determined in longitude, and a cause of error lies in the determination of the trend of the crest and the associated magnetic anomalies. For this reason, in this paper, the adopted positions of the centers of rotation are those obtained from the azimuths of the fracture zones.

Acknowledgments. The data on which this paper is based were obtained over many years by Lamont ships, and their collection involved many scientists under the general direction of M. Ewing. The collection of magnetic data was supported by the Office of Naval Research (contract NO 0014-67-A-0108-0004) and the National Science Foundation (grants GP-5536 and GA-894). This research was supported by the Office of Naval Research and the National Science Foundation (grant GA-580). J. Heirtzler initiated the investigation. Discussions with many colleagues were useful, in particular, G. Bryan, G. Dickson, T. Edgar, J. Ewing, M. Ewing, M. Langseth, W. J. Morgan, N. Opdyke, W. Pitman, W. Sheridan, L. Sykes, and M. Talwani. G. Dickson, E. Herron, M. Mayhew, W. Pitman, and T. Saito kindly gave me access to unpublished data. M. Ewing, J. Oliver, and M. Talwani reviewed the final manuscript.

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(Received January 2, 1968.)