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Spreading of the Ocean Floor: New Evidence

Magnetic anomalies may record histories of the ocean basins and Earth's magnetic field for 2×10^8 years.

F. J. Vine

Controversy regarding continental drift has raged within the earth sciences for more than 40 years. Within the last decade it has been enlivened by the results of paleomagnetic research and exploration of the ocean basins (*1*). Throughout, one of the main stumbling blocks has been the lack of a plausible mechanism to initiate and maintain drift. Recently, however, the concept of spreading of the ocean floor, as proposed by Hess (*2*), has renewed for many the feasibility of drift and provided an excellent working hypothesis for the interpretation and investigation of the ocean floors. The hypothesis invokes slow convection within the upper mantle by creep processes, drift being initiated above an upwelling, and continental fragments riding passively away from such a rift on a conveyor belt of upper-mantle material; movements of the order of a few centimeters per annum are required. Thus the oceanic crust is a surface expression of the upper mantle and is considered to be derived from it, in part by partial fusion, and in part by low-temperature modification. This model, as developed by Hess and Dietz (*3*), can be shown to account for many features of the ocean basins and continental margins.

It seems reasonable to assume that, if drift has occurred, some record of it should exist within the ocean basins. Heezen and Tharp (*4*) have delineated north-south topographic scars on the floor of the Indian Ocean that may well be caused by the northward drift of India since Jurassic time. Wilson (*5*) has suggested that drift and ocean-floor spreading in the South Atlantic and East Pacific may be recorded in the form of fracture zones and aseismic volcanic ridges. It has also been postulated that the history of a spreading ocean floor may be recorded in terms of the permanent (remanent) magnetization of the oceanic crust.

Vine and Matthews (*6*) have suggested that variations in the intensity and polarity of Earth's magnetic field may be "fossilized" in the oceanic crust, and that this condition in turn should be manifest in the resulting short-wavelength disturbances or "anomalies" in Earth's magnetic field, observed at or above Earth's surface. Thus the conveyor belt can also be thought of as a tape recorder. As new oceanic crust forms and cools through the Curie temperature at the center of an oceanic ridge, the permanent component of its magnetization, which predominates, will assume the ambient direction of Earth's magnetic field. A rate of spreading of a few centimeters per annum and a duration of 700,000 years for the present polarity (*7*) imply a central "block" of crust, a few tens of kilometers in width, in which the magnetization is uniformly and "normally" directed. The adjacent blocks will be of essentially reversed polarity, and the width and polarity of blocks successively more distant from the central block will depend on the reversal time scale for Earth's field in the past.

Vine and Wilson considered that the bulk of the magnetization resides in a comparatively thin layer, 1 or 2 kilometers of basaltic extrusives and intrusives, coating a main crustal layer of serpentinite (*8*). If the frequency of extrusion and intrusion of this material is approximately normally distributed about the axis of the ridge (*9*), all blocks other than the central block will be contaminated with younger material, possibly of opposite polarity, in which case their bulk resultant or effective magnetization will be reduced. In this way a model has been developed in which the magnetization of the central block is assumed to be twice that of the others. This model derives from work on a very small but detailed survey of an area on the crest of Carlsberg Ridge in the northwest Indian Ocean (*10*).

The idea was an attempt to explain two interesting and enigmatic features of oceanic magnetic anomalies: the well-known central anomaly associated with the axes of ridges, first observed by Ewing, Hirshman, and Heezen (*11*); and the remarkable striped pattern of anomalies revealed by surveys of Earth's magnetic field in the northeastern Pacific (for example, Fig. 1). These anomalies are known to retain their characteristic shape and spacing for thousands of kilometers along their length (*12*) and are quite unlike anomalies observed over the continents. They are very difficult to simulate if one assumes any reasonable lithologic contrasts within the oceanic crust, or plausible geologic structures. Intuitively it was felt that in some way the anomalies must be a surface expression of convection within the mantle. The thesis assumes therefore that the linear anomalies of the northeastern Pacific

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are quite ubiquitous over the deep ocean basins; that they are interrupted only by anomalies associated with isolated seamounts or volcanic ridges, and by fracture zones which offset the anomaly pattern—as was shown by Vacquier in the northeast Pacific (*12*).

Of the three basic assumptions of the Vine and Matthews hypothesis, field reversals (*7*) and the importance of remanence (*13*) have recently become more firmly established and widely held; thus in demonstrating the efficacy of the idea one might provide virtual proof of the third assumption: ocean-floor spreading, and its various implications.

Difficulties

At the time this concept was proposed there was very little concrete evidence to support it, and in some ways it posed more problems than it solved. There were, for example, at least three rather awkward points that it did not explain:

1) Many workers felt and feel that the northeast Pacific anomalies do not parallel any existing or preexisting oceanic ridge (*14*).

2) Whereas one can visually correlate anomalies on widely spaced profiles in the northeastern Pacific, one cannot do this over ridge crests, except for the central anomaly. Vacquier (*12*) maintained, therefore, that there are no linear anomalies paralleling the central anomaly over the crests of ridges.

3) The idea did not, very obviously, explain the fact that the low-amplitude, short-wavelength anomalies observed on either side of the axis of a ridge give way to higher-amplitude, long-wavelength anomalies over the more distant flanks—an observation originally made by Vine and Matthews (*6*) and emphasized by Heirtzler and Le Pichon (*15*). With the increase in depth of the magnetic material as one moves from the ridge crest to the flanks, one would expect disappearance of shorter wavelengths but not an increase in amplitude.

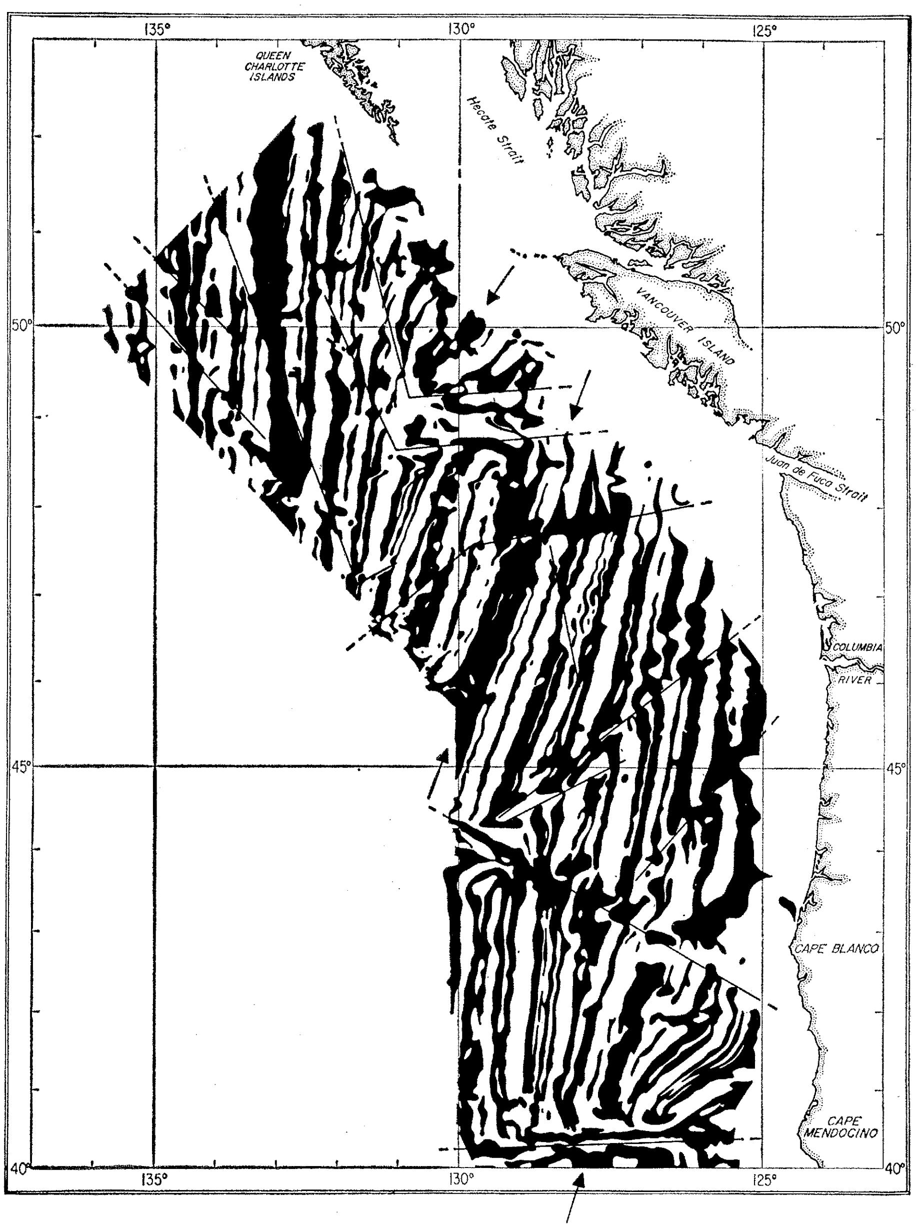
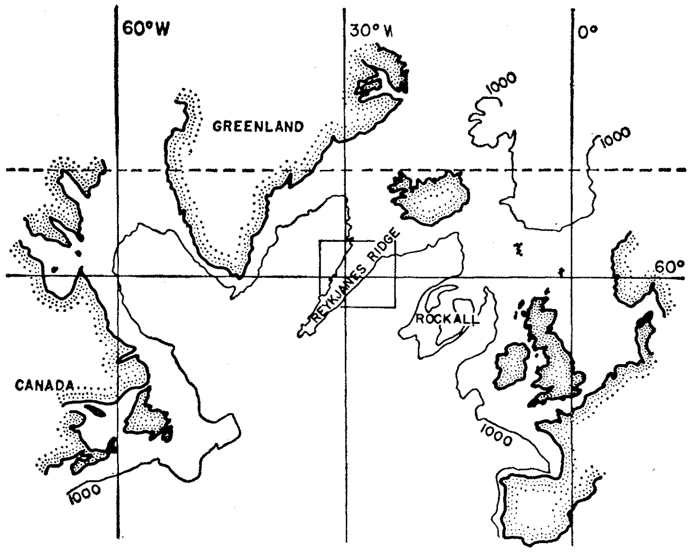


Fig. 1. Summary diagram of total magnetic-field anomalies southwest of Vancouver Island. Areas of positive anomaly are shown in black. Straight lines indicate faults offsetting the anomaly pattern; arrows, the axes of the three short ridge lengths within this area—from north to south, Explorer, Juan de Fuca, and Gorda ridges. See also Fig. 15. [Based on fig. 1 of Raff and Mason (*27*); courtesy Geol. Soc. Amer.]

Corollaries

The second difficulty is clearly rather fundamental, but has persisted because until recently no large, detailed survey of the crest of a midocean ridge was thought to be available. However, in 1963 the U.S. Naval Oceanographic Office (*16*) made a detailed aeromagnetic survey of Reykjanes Ridge, southwest of Iceland (Fig. 2) (*17*). The ridge was chosen because it clearly forms part of the northerly extension of the Mid-Atlantic Ridge through Iceland, and because earlier traverses had indicated a typical central anomaly over its crest (*18*). A diagram summarizing the anomalies revealed by this survey appears in Fig. 3. The area summarized, approximating a 400-kilometer square, shows a pattern of linear anomalies paralleling the central anomaly and symmetrically disposed about it. This finding, together with the symmetry and linearity of the magnetic anomalies about the Juan de Fuca and Gorda ridges (Fig. 1), recently described by Wilson (*19*), provides convincing confirmation of the two most obvious corollaries of a literal interpretation of the Vine-Matthews hypothesis: (i) linear magnetic anomalies should parallel or subparallel ridge crests, and (ii) for many latitudes and orientations the anomalies should be symmetric about the axis of the ridge.

If one pursues a literal application of the idea, a further possibility is simulation of anomalies at ridge crests by assuming the reversal time scale for the last 4 million years proposed by Cox, Doell, and Dalrymple (*7*), the



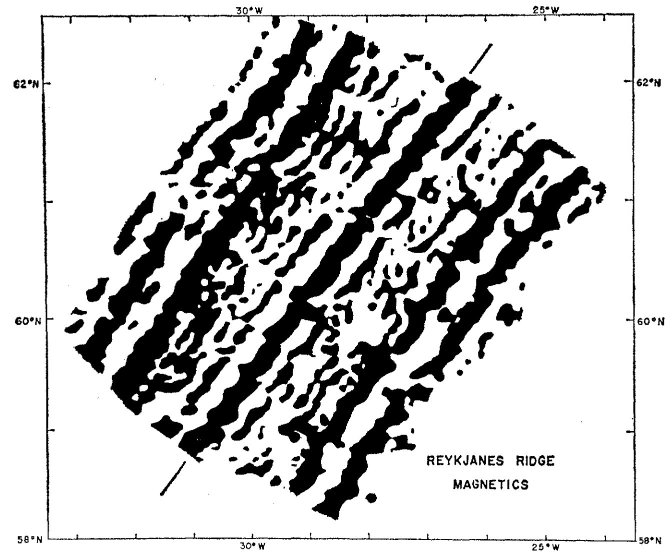


Fig. 2 (left). The location of Reykjanes Ridge, southwest of Iceland, and the area of Fig. 3. The 1000-fathom submarine contour is shown, together with the 500-fathom contours for Rockall Bank. Fig. 3 (right). Summary diagram of the magnetic anomalies observed over Reykjanes Ridge (see Fig. 2). Straight lines indicate the axis of the ridge and the central positive anomaly (*17*).

only additional parameter being the rate of spreading; the scale (Fig. 4) has recently received striking independent confirmation from the work of Opdyke *et al.* (*20*) on deep-sea sedimentary cores.

Reykjanes Ridge

Observed anomaly profiles obtained during four crossings of the crest of Reykjanes Ridge are compared (Fig. 5) with simulations obtained by assumption of reversal time scales for the last 4 million years and a rate of spreading of 1 centimeter per annum for each limb of the ridge. The model assumed is analogous to the one I have described (*8*, model 2), but the depths have been made compatible with the depth to the ridge crest in this area and with the altitude at which the survey was flown. In performance of the survey, 58 parallel courses were flown normal to the ridge axis, but the crest was not traversed by the first four and last five courses: thus crossings 15, 25, 35, and 45 are shown as being representative. The correlation between the observed and computed anomalies is very encouraging and suggests a rate of spreading of rather less than 1 centimeter per annum.

When one applies the concept of continental drift to this region, it seems reasonable to assume that Rockall Bank, southeast of the ridge (Fig. 2), is a continental fragment, as was assumed by Bullard, Everett, and Smith (*21*) in reconstructing the fit of the continents around the Atlantic. In this instance the deep to the southeast of Rockall may represent an initial abortive split; the oceanic area to the northwest, centered on Reykjanes Ridge, a subsequent and more persistent site of spreading of the ocean floor. There is every indication from the existing bathymetry (*17*) that the ridge crest is linear and not interrupted or offset by transverse fractures.

This area therefore, 1200 kilometers in width, may well record a comparatively simple and straightforward example of drifting and spreading. The oldest rocks in the Thulean or Brito-Arctic Tertiary Igneous province occur in northwestern Scotland and eastern Greenland. Preliminary potassium-argon dates from Arran, Mull, and other centers in the British Isles suggest an age of approximately 60 million years (perhaps slightly greater) (*22*). If it is assumed that this igneous activity indicates the initiation of drift in this area, then the implied average rate of spreading from Reykjanes Ridge (half width, 600 km) is approximately 1 centimeter per annum —that is, the rate of "drifting" is approximately 2 centimeters per annum.

Other Ridges

The model proposed by Vine and Matthews (*6*) and developed by Vine and Wilson (*8*) has been applied to four widely separated areas on the midoceanic ridge system (Figs. 6–9) by assumption of the reversal time scale shown in Fig. 4 and a rate of spreading compatible with the width of the central anomaly. An observed profile across Juan de Fuca Ridge, southwest of Vancouver Island (Fig. 1) (*8, 19*), is compared (Fig. 6) with a simulated profile based on a rate of spreading of 2.9 centimeters per annum per limb of the spreading system. A profile across the East Pacific Rise, just north of the Eltanin Fracture Zone (*23*), is compared (Fig. 7) with a computed profile based on a rate of spreading of 4.4 centimeters

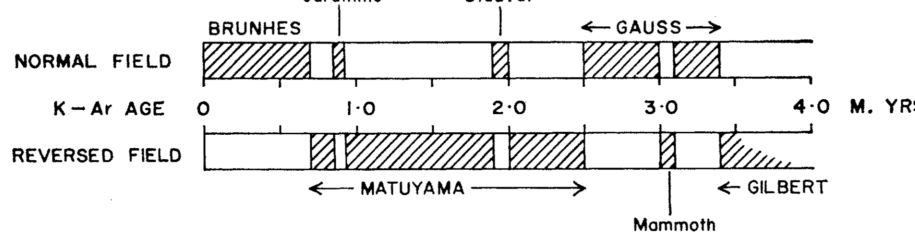


Fig. 4. Geomagnetic-polarity epochs deduced from paleomagnetic results and potassium-argon dating. [Based on Cox, Doell, and Dalrymple, and Doell and Dalrymple (*7*)]

per annum. Clearly this rate, implying a rate of separation of nearly 9 centimeters per annum, is an order of magnitude greater than the commonly quoted rates of 1 or 2 centimeters per annum; the significance and possible implications of this difference are discussed later.

Observed profiles across Carlsberg Ridge in the northwest Indian Ocean and across the Mid-Atlantic Ridge in the South Atlantic are compared (Figs. 8 and 9) with simulations based on a rate of spreading of 1.5 centimeters per annum. As Backus has pointed out (*24*), one may expect the width of the anomalies in the South Atlantic to increase southward, reflecting a progressive increase in the rate of spreading, because of the rotation of South America relative to Africa (*21*) and the resultant southward increase in separation. The increase southward, in the width of the envelope of the central magnetic anomalies indicated by Heirtzler and Le Pichon (*15*, fig. 3), may well be an expression of this phenomenon.

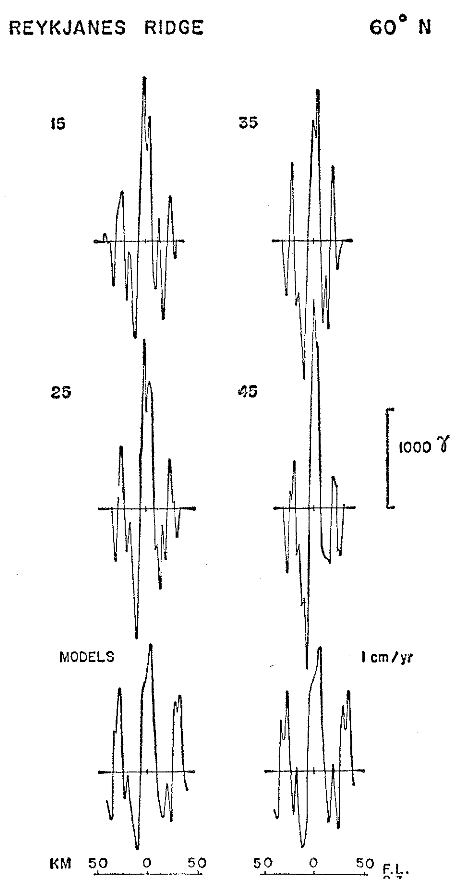


Fig. 5. Profiles observed across Reykjanes Ridge, together with computed profiles. The model to the left assumes the reversal time scale of Fig. 4; that to the right, the "revised" time scale of Figs. 12 and 13 (*45*). All observed and computed profiles have been drawn to the same proportion; 10 kilometers horizontally is equivalent to 100 gamma vertically (1 gamma = 10^{-5} oersted). *F.L.*, flight level.

The Red Sea

In Fig. 10 a modification of the model has been applied at two points on the Red Sea rift. If the axial depression and zone of magnetic anomalies in the Red Sea are considered to indicate the initiation of continental drift by spreading of the ocean floor (*25*), then clearly such a simulation should be attempted. However, the depth to this embryonic ocean floor and its crustal section (*26*) are not typical of an oceanic ridge, and this floor almost certainly includes some assimilated or floundered continental material.

In Fig. 10 a slightly thickened "volcanic" layer has been truncated against nonmagnetic continental material according to the width of the central depression and anomalies at each point. The same rate of spreading, 1 centimeter per annum, has been assumed at both points, hence the different lengths of the reversal time scale involved.

One would not expect the anomaly pattern in the Red Sea rift to be as clear-cut as that over the more mature Juan de Fuca or Reykjanes ridges; nevertheless the approximation of the simulated to the observed anomalies is encouraging. The dates of rifting implied from these models should not be taken to indicate the initiation here of crustal extension. In initiating drift in a typical shield area (that is, beneath possibly 35 kilometers of continental crust, in this area), an upwelling in the mantle may well start by producing "necking" (thinning) of the crust, normal faulting, and intrusion and extrusion of basic igneous material —all effects producing extension and thinning of the crust and the possibility of marine transgression prior to the initiation of drift and the emplacement of quasi-oceanic crust.

The Reversal Time Scale

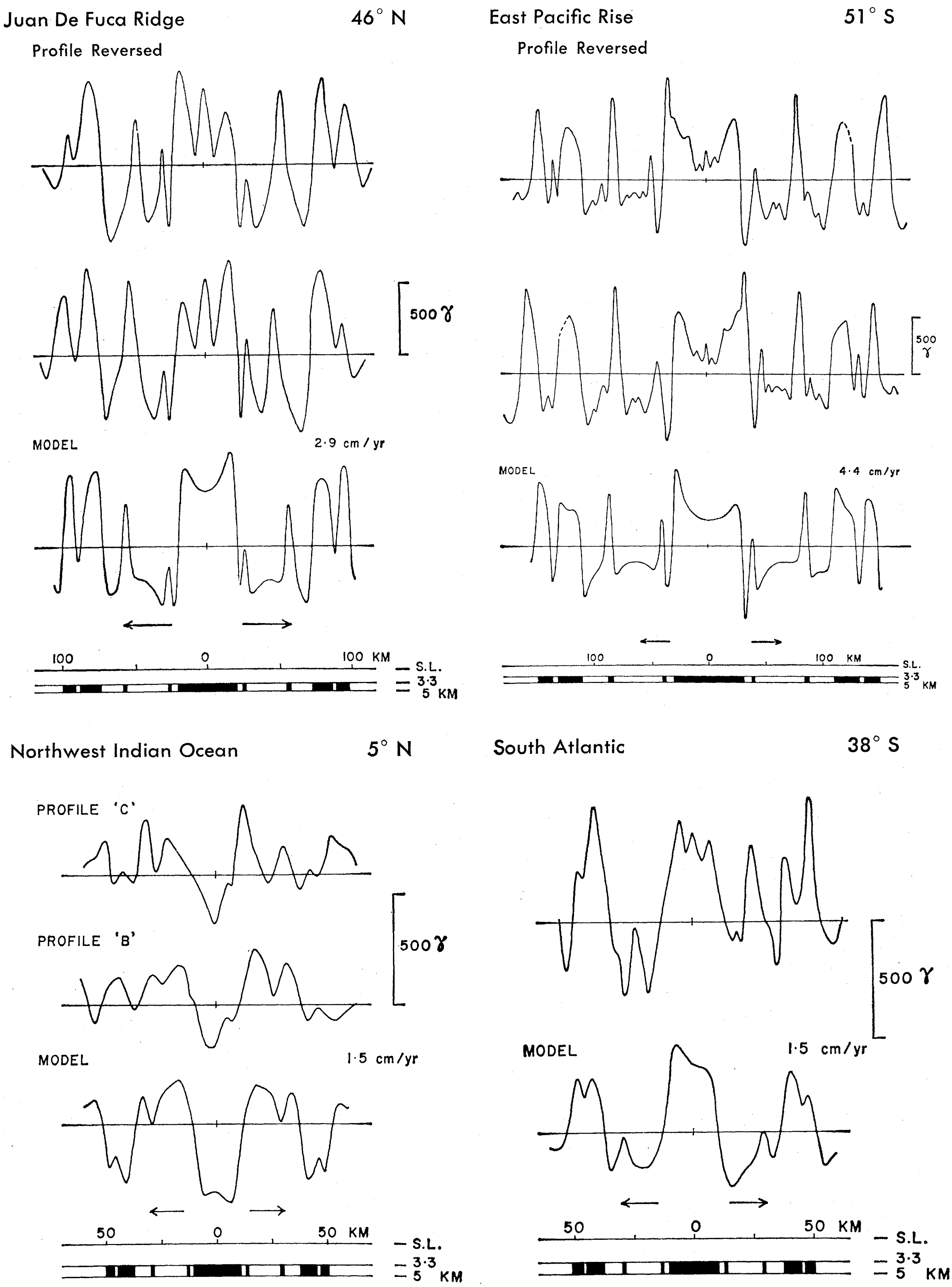
In simulating the anomalies observed centrally over oceanic ridges, in terms of normal-reverse boundaries within the oceanic crust, one can deduce these boundaries independently without reference to a reversal time scale (*8*). In Fig. 11 boundaries inferred from the observed profiles across the East Pacific Rise and Juan de Fuca and Reykjanes ridges (Figs. 5–7) are plotted against the reversal time scale of Cox, Doell, and Dalrymple (*7*), according to their distances from the axis of the ridge. The dashed line in this graph indicates a similar plot for the boundaries at the Juan de Fuca Ridge and the time scale assumed by Vine and Wilson (*8*).

In this earlier time scale the Jaramillo event (Fig. 4) had not been differentiated, and the most recent reversal was placed at 1 million years ago. Consequently the narrow peaks on either side of the central positive anomaly in Fig. 6 were correlated with the Olduvai event. This correlation implied a very erratic rate of spreading and a much slower average rate of 1.5 centimeters per annum (*8*).

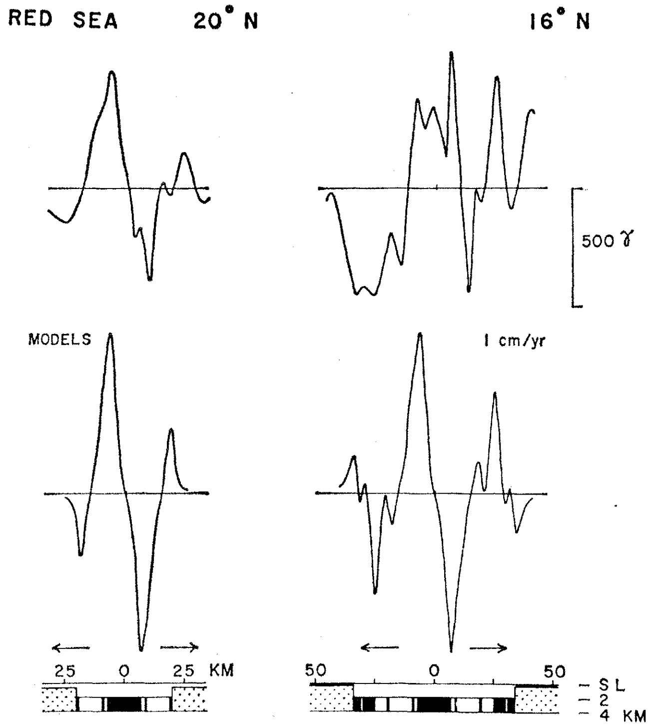
It will be seen that, had the authors had more faith in the idea and the probability of a more constant rate of spreading, for inertial reasons, they could have predicted the Jaramillo event. The recent detailing of this event by Doell and Dalrymple (*7*) and its independent discovery by Opdyke *et al.* (*20*) are therefore of considerable interest and importance in interpretation of the magnetic anomalies.

On correlation of the crustal boundaries with the new time scale (Fig. 11), the implied rates of spreading are more constant and much faster than before. Moreover, rather remarkably, the deviations from linearity for the East Pacific Rise and Juan de Fuca Ridge—11,000 kilometers apart—are exactly analogous. The only discrepancy occurs in the region of the Mammoth event, concerning which there is a suggestion, from the profile resulting

Figs. 6–9 (facing page). Observed magnetic profiles at various points on the midocean ridge system are compared with simulated profiles based on the reversal time scale of Fig. 4, a constant rate of spreading, and the model outlined in the text (*47*). The observed profiles are taken from Raff and Mason (*27*, pl. 1) for Juan de Fuca Ridge [see also Vine and Wilson (*8*, fig. 3)]; the *Eltanin*-19 profile (East Pacific Rise) of Pitman and Heirtzler (*23*, fig. 2); the Owen profiles (northwest Indian Ocean) of Matthews, Vine, and Cann (*46*, fig. 2); and the Zapiola-2 profile (South Atlantic) of Heirtzler and Le Pichon (*15*, fig. 1). *S.L.*, sea level.



Juan De Fuca Ridge
46° N
Profile Reversed
500 γ
MODEL
2·9 cm / yr
100
0
100 KM
S.L.
3·3
5 KM
East Pacific Rise
51° S
Profile Reversed
500 γ
MODEL
4·4 cm/yr
100
0
100 KM
S.L.
3·3
5 KM
Northwest Indian Ocean
5° N
PROFILE 'C'
PROFILE 'B'
500 γ
MODEL
1·5 cm/yr
50
0
50 KM
S.L.
3·3
5 KM
South Atlantic
38° S
500 γ
MODEL
1·5 cm/yr
50
0
50 KM
S.L.
3·3
5 KM



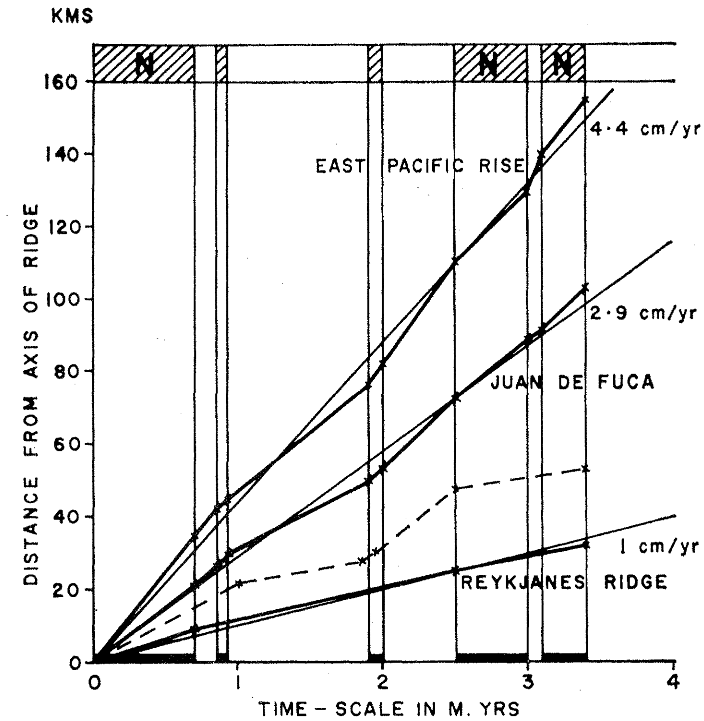


Fig. 10 (left). Observed profiles across the Red Sea [from Allan, Charnock, and Morelli (*48*); Drake and Girdler (*26*)] compared with computed profiles based on a constant rate of spreading and a truncated model and time scale according to the width of the central depression and zone of magnetic anomalies (*49*). Stippled area, "nonmagnetic" continental material. Fig. 11 (right). Inferred normal-reverse boundaries within the crust plotted against the reversal time scale of Fig. 4. The dashed line represents a similar plot for Juan de Fuca Ridge, if one assumes the earlier time scale—as did Vine and Wilson (*8*). Note the similar deviations from linearity for the East Pacific Rise and Juan de Fuca Ridge.

from the very fast rate of spreading in the South Pacific (Fig. 7), that this event is multiple; that is, it may include a short period of normal polarity (see Fig. 13).

If, therefore, one assumes constant rates of spreading for these two areas (the averages obtained from Fig. 11), one can replot the inferred boundaries on lines of constant spreading rates and suggest slight revisions of the reversal time scale, as are shown in Fig. 12. Clearly, much more data should be analyzed in this way to confirm or invalidate this type of revision, but it presents an interesting possibility.

In discussing the magnetic anomalies associated with Juan de Fuca Ridge, Vine and Wilson compared a profile across this ridge with the only available profile across the East Pacific Rise (*8*, fig. 2). This rather rash comparison has now been vindicated by the publication of four new profiles across the East Pacific Rise by Pitman and Heirtzler (*23*) (see also Figs. 6 and 7). Of these new profiles, the *Eltanin*-19 profile (Fig. 14) shows, as Pitman and Heirtzler emphasized, remarkable symmetry about its midpoint; it is presumably most suitable for deduction of the frequency and occurrence of reversals in the Pliocene. Thus, if one assumes the rate of spreading obtained centrally from this profile (Fig. 11) and deduces normal-reverse boundaries in the crust out to a distance of 500 kilometers, one can suggest a reversal time scale for the last 11.5 million years (Fig. 13).

This extrapolation clearly depends on the continued applicability of the model and a constant rate of spreading, but it presents at least two very interesting possibilities: (i) it can be compared with the time scales obtained by other techniques as these scales are extended back into the Pliocene (*7, 20*); and (ii) if the Vine-Matthews hypothesis is applicable to all active oceanic ridges as has been suggested, one can use this time scale to simulate and predict central anomalies at other latitudes and orientations of the ridge system, as is illustrated for the time scale out to 4 million years in Figs. 5–10. Pitman and Heirtzler's (*23*) simulation, of the type suggested, for Reykjanes Ridge agrees very well with the observed profile.

The East Pacific Rise

In the Pacific, where the spreading rate appears to be much faster, many details of the reversal time scale are apparent: For example, the four positive peaks associated with the periods of normal polarity between 4 and 5 million years ago, and the broad positive resulting from the period between 9 and 10 million years ago, are clearly identifiable in Fig. 1, together with other details of the time scale, centered on Juan de Fuca and Gorda ridges.

The area covered by this survey appears to be transected by many transcurrent or transform faults, or both, separating apparently rotated blocks, as Raff and Mason (*27*) and Wilson (*19*) suggested. However, if one takes into consideration the offset of the anomaly pattern across these faults, one can reconstruct a profile across and to the northwest of Juan de Fuca Ridge (Fig. 14), and this profile remarkably resembles the one obtained in the South Pacific, 11,000 kilometers away. Furthermore, if one deduces boundaries within the crust from the Juan de Fuca profile and plots these on the vertical time lines obtained from the South Pacific profile in Fig. 13, there is a suggestion that the rate of spreading in the Juan de Fuca area may have decreased within the Pliocene from a rate of 4 or 5 to 2.9 centimeters per annum for the last 5.5 million years.

Clearly one cannot distinguish between an acceleration of the East Pacific Rise in the South Pacific and a deceleration of Juan de Fuca Ridge in the north, but the latter is considered more likely and leads to an interesting speculation.

The anomalous width and unique features of the American Cordillera in the western United States were emphasized by Wise (*28*), who considered that these features may be related to, or at least reflected in, the apparently rotated oceanic crustal blocks revealed by the magnetic survey (Fig. 1). Wise felt that his hypothesis was outrageous, but I should like to develop it further in the light of this reinterpretation of the magnetic anomalies.

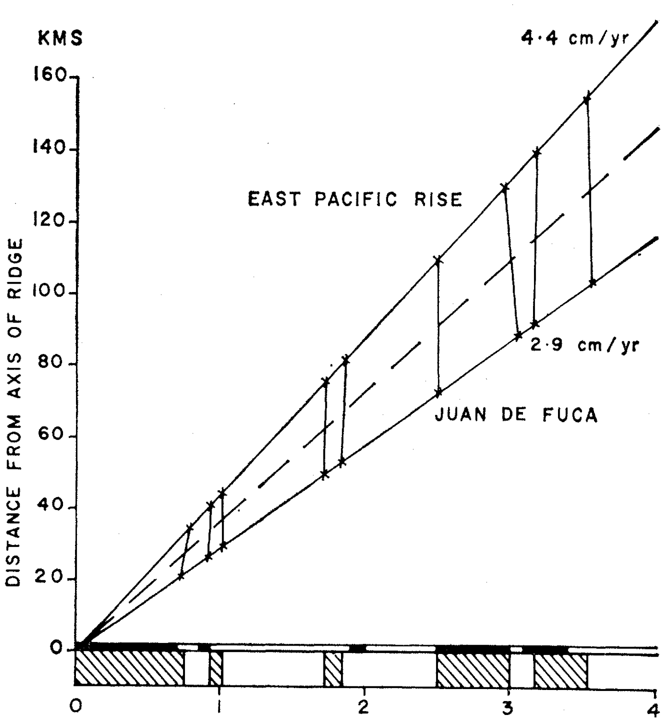
I suggest that, to a first-order approximation, the more recent geologic history and structures of the western United States can be ascribed to the progressive westward drift of the North American continent away from the spreading Atlantic Ridge, and to the fact that the continent has overridden and partially resorbed first the trench system and more recently the crest of the East Pacific Rise.

As Hess has noted on the basis of ocean-floor spreading (*3*), only ridges that have been initiated beneath continents, and that are therefore actively causing continents to drift apart, should be approximately median within the ocean basins. Pacific ridges such as the extinct Darwin Rise and the active East Pacific Rise are not constrained in this way, having been initiated presumably in oceanic areas. Therefore I follow Menard (*29*) and Wilson (*5*) in maintaining that the northeast Pacific basin represents a flank of the East Pacific Rise, the crest of which has been modified, and arrested by the encroachment of North America.

The former east-west direction of spreading from the East Pacific Rise, reflected in the north-south magnetic anomalies of the northeast Pacific, has apparently been replaced within the Pliocene so that the present direction of motion is northwest-southeast, paralleling the San Andreas fault, as Wilson (*30*) suggested.

In the area off Washington and Oregon and to the north of the Mendocino Fracture Zone, this change in direction has been accommodated by faulting and a gradual stifling and reorientation of the ridge crest to form Juan de Fuca and Gorda ridges. This stifling is illustrated by profiles in Fig. 14, but it is most graphically shown by coloring the anomaly bands of Fig. 1 with a spectrum of colors according to their ages. Such a diagram reveals another short and less obvious ridge to the north of Juan de Fuca Ridge, as is indicated in Figs. 1 and 15; the short ridge, like the Gorda, has a pronounced topographic expression (*31*), particularly near the continental margin, where the central magnetic pattern is also clearest. The proximity of this new ridge to the Explorer seamount and the Explorer trench (*31*) has led to its name: Explorer Ridge (see Fig. 15).

South of Cape Mendocino, current crustal spreading appears to be accommodated along the San Andreas fault, as was proposed by Wilson (*30*). In this area, between the Mendocino and Murray fracture zones, the former ridge crest has presumably been overridden and damped out, perhaps not without attempts at modification as suggested by the northeasterly trending anomalies, near the continental margin, in the magnetic survey of this area (*32*) (see Fig. 15). However, it is interesting to reconstruct the ridge crest as it would be had it not been overridden and modified. If one calculates the position of the ridge crest



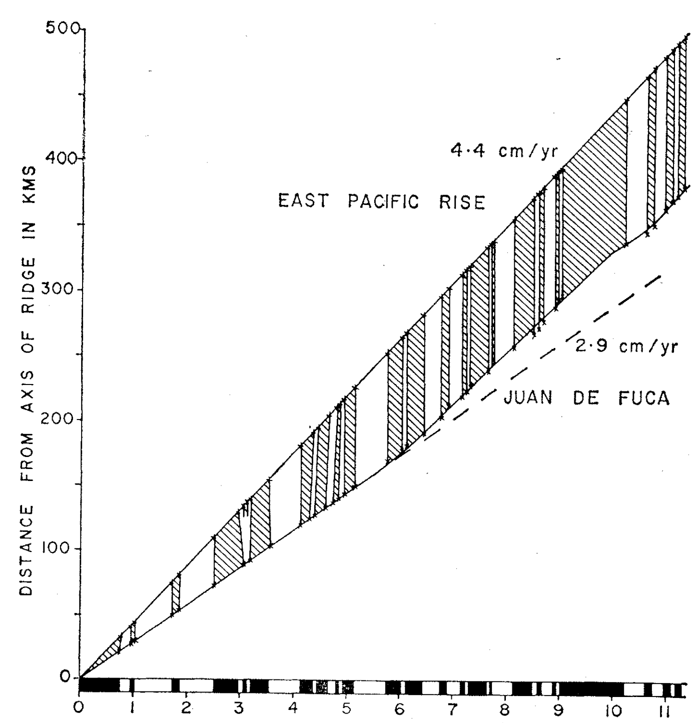


Fig. 12 (left). Crustal boundaries replotted along lines of constant rates of spreading (that is, best-fitting straight lines in Fig. 11); slight revision of the reversal time scale are suggested. The "revised" time scale is the lower, ruled scale. Fig. 13 (right). Magnetic boundaries across the East Pacific Rise, deduced out to 500 kilometers from the crest and plotted on a line representing a constant spreading rate of 4.4 centimeters per annum. Similar boundaries from Juan de Fuca Ridge are plotted out to 150 kilometers on the assumption of a constant spreading rate of 2.9 centimeters per annum. The time scale out to 5.5 million years is based on both plots. Beyond that time the time scale is based on the East Pacific Rise boundaries, and those deduced from Juan de Fuca Ridge are simply plotted on these time lines.

north of the Mendocino (had it not been stifled) and assumes the offsets measured further west on the Mendocino and Pioneer fractures (*12*), the reconstructed ridge crest lies beneath Utah and Arizona—the area of the Colorado Plateau uplift (see Fig. 15).

South of the Murray fracture zone the picture is less clear; possible clues from the oceanic magnetic anomalies are still confused because of the lack of an extensive survey. However, from the very nature of the Gulf of California, from its close analogy with the Gulf of Aden (*33*), and in the light of the important observation by Menard that the Clipperton fracture zone does not offset the present crest of the East Pacific Rise (*34*), it seems probable that this length of the present crest, at least as far south as the Clipperton fracture, is new and not a modification of the former crest, as are Juan de Fuca and Gorda ridges.

This interpretation of the present crustal motion in the northeast Pacific, involving transform faults (*30*) and northwest-southeast movement, seems to accord with the anomalous nature of the circum-Pacific belt between Mexico and Alaska. This region lacks trench systems and their associated planes of deeper-focus earthquakes—an observation underlined by Girdler (*35*), and a fact perhaps precluding east-west or northeast-southwest compression. I must emphasize that my evidence (essentially contained in Fig. 14) suggests that this change in direction occurred within the last 10 million years and that earlier, for example, quasi-transform faults may have existed along the continental extension of the Mendocino and Pioneer fracture zones, producing the right lateral offset of the various tectonic belts indicated by Wise (*28*) (see Fig. 15).

Thus the north-south magnetic anomalies of the northeast Pacific are considered to be related to a former crest of the East Pacific Rise. Further support for this hypothesis comes from the flank anomalies. New data (*36*) have enabled Peter (*37*) to trace a particular pattern of flank anomalies approximately from north to south from the Aleutian trench to just south of the Murray fracture zone, a distance of 2800 kilometers; the top two profiles in Fig. 16 illustrate the pattern along latitudes 35°40′ and 36°30′N (*37*). Christoffel and Ross (*38*), working south of New Zealand, have similarly correlated flank anomalies on adjacent north-south profiles at approximately 173°E (Fig. 16). It is suggested that the two patterns are the same except for difference in the rate of spreading that formed them. The two areas are 11,000 kilometers apart.

In addition, the pattern to the south of New Zealand bears the same relation to the New Zealand Plateau, the presumed northern boundary of the East Pacific Rise in this area, as the northeast Pacific pattern bears to the western boundary of the north-south anomalies suggested by Raff and Peter (*37*). Judged from the lengths of the patterns in the two areas (Fig. 16), the ratio of the rates of spreading was

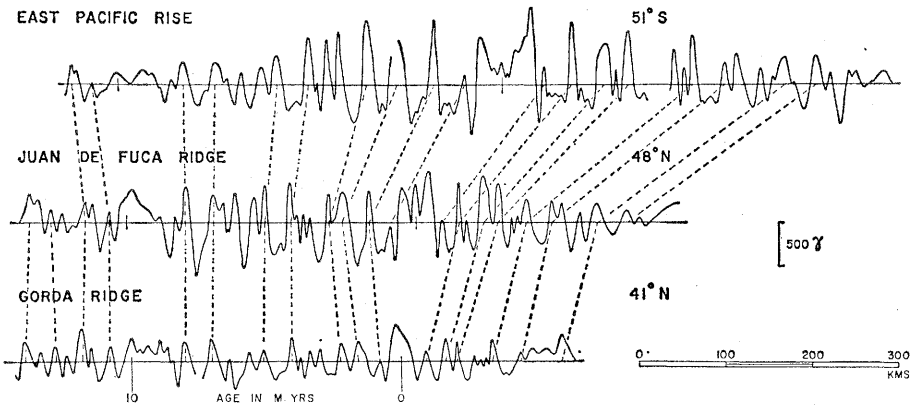


Fig. 14. The East Pacific Rise profile *Eltanin*-19 [Pitman and Heirtzler (*23*)] compared with a composite profile across and to the northwest of Juan de Fuca Ridge, and with a profile normal to the strike of the anomalies across and to the west of Gorda Ridge. [The last two profiles from Raff and Mason (*27*) and Vacquier *et al.* (*50*)]

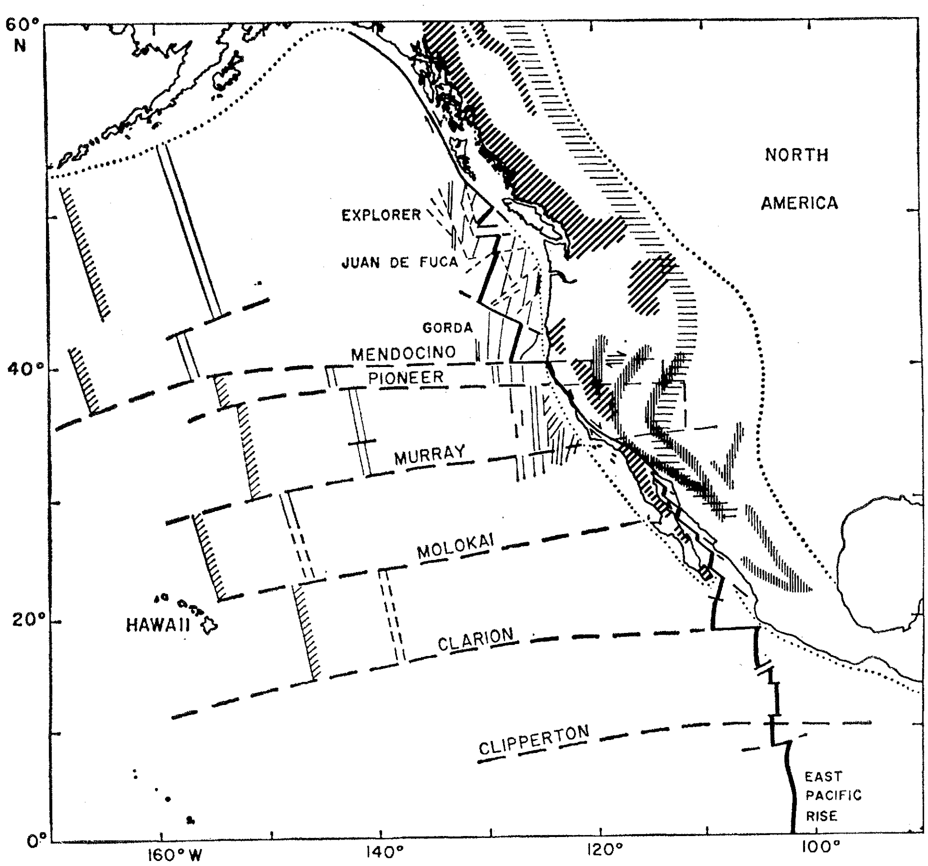


Fig. 15. The East Pacific Rise in the North Pacific. Solid black lines indicate the present crest and active transform faults [the crest south of the Gulf of California, from Menard (*34*)]. Thin lines represent key magnetic anomalies: in particular, the pair of anomalies traced by Peter (*37*) between 160° and 140°W. The half-herringbone pattern to the west suggests a possible boundary of the rise and its associated north-south magnetic anomalies. Broken lines indicate inactive faults or fractures. Dotted lines enclose the circum-Pacific cordillera within which the tectonic belts of Wise (*28*) are shown by ruled shading.

3 : 2 at the time of formation. In the South Pacific and to the south of New Zealand the width of the East Pacific Rise decreases southwestward, the decrease implying slower rates of spreading. This implication was supported by crossings of the ridge in this area by U.S.S. *Staten Island* in 1961 (*39*), showing that the width of the central anomalies also decreases southwestward.

The fast rate of spreading that I suggest for the East Pacific Rise has two important implications regarding its heat budget: (i) any systematic variation in the heat flow, caused by convection beneath, should be much clearer here than in the Atlantic or Indian Oceans; and (ii) the elevation of the Rise, which is presumably related to thermal expansion or partial fusion within the upper mantle, should persist to greater distances from its crest—as it appears to do.

Earth's Paleofield

I have demonstrated that the fast rate of spreading in the Pacific shows up incredible details in the reversal time scale out to at least 4 and perhaps 11 million years ago. If one assumes that the rate has always been high (4 to 5 cm/year) and that the hypothesis continues to apply, changes in the intensity and polarity of Earth's magnetic field during the remainder of the Tertiary should be recorded in the oceanic crust and associated magnetic anomalies, out to the boundary of the East Pacific Rise.

Immediately north of the Mendocino fracture zone one can reconstruct such a profile from the crest of Gorda Ridge to the boundary of the north-south anomalies at 168°W. This profile (Fig. 17) has been calibrated with a suggested time scale beyond 10 million years, on the basis of a constant rate of spreading of 4.5 centimeters per annum. Thus it is implied that the East Pacific Rise, at least in the north and south, and perhaps throughout the length of the Pacific, was initiated in the late Cretaceous, possibly at the time of the extinction and beginning of subsidence of the Darwin Rise (*29*).

Furthermore, the profile of Fig. 17, since it implies a particular sequence of normal-reverse boundaries and changes in bulk magnetization within the crust, may enable one to predict and correlate anomalies in other oceanic areas, just as one could, from the South Pacific profile, for the North Pacific (Fig. 14) and North Atlantic (*23*); in fact, until this is done, the speculative nature of this time scale cannot be overemphasized.

Ridges in other oceanic areas have been initiated beneath continents, and

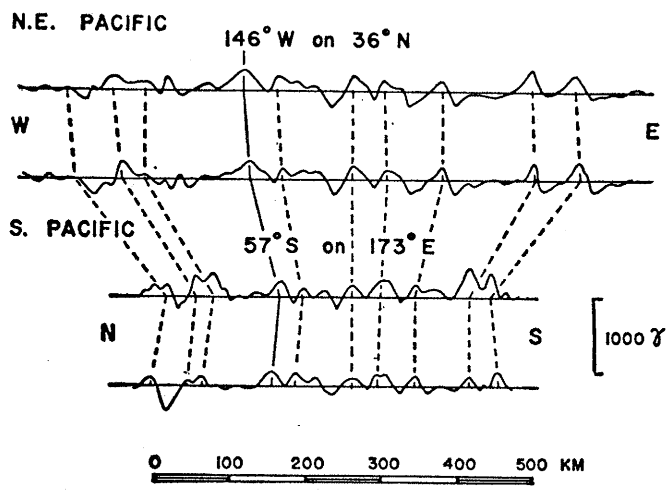
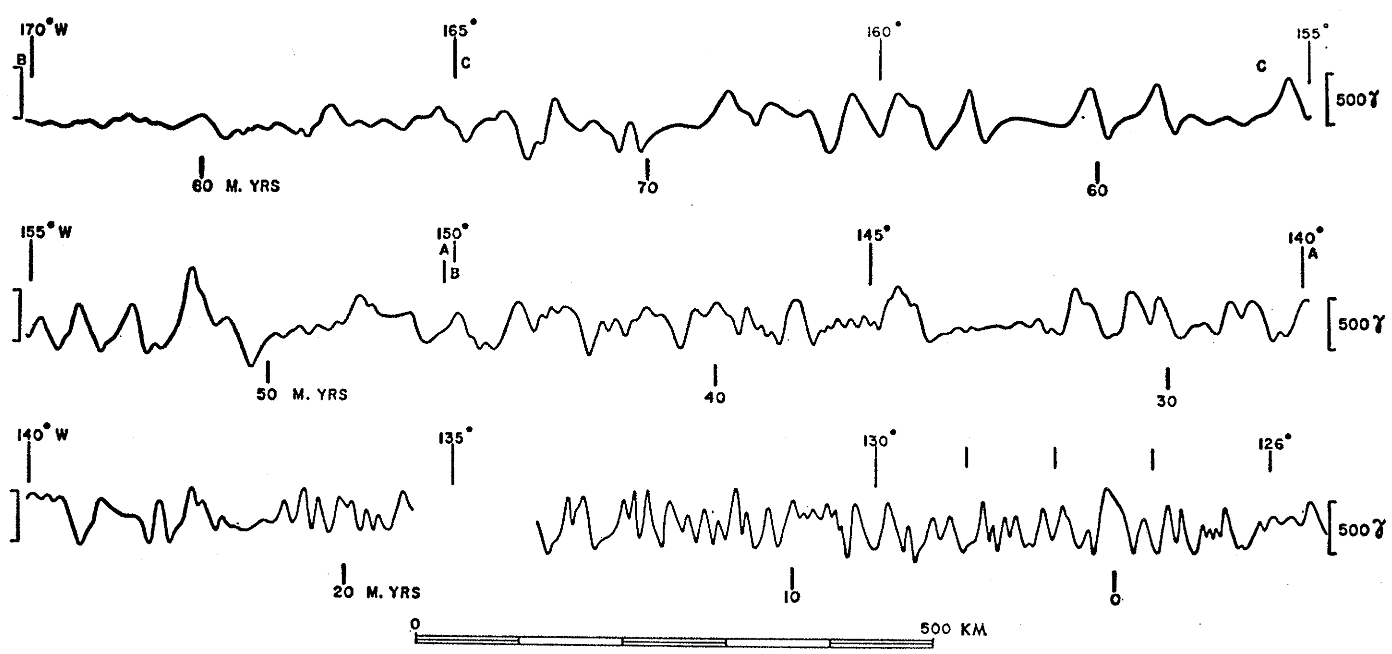


Fig. 16 (left). The anomaly pattern correlated between profiles by Peter and Raff in the North Pacific (*37*) and Christoffel and Ross in the South Pacific (*38*). It is suggested that the only difference between the two is the rate of spreading that formed them.

Fig. 17 (below). East-west profile immediately north of the Mendocino Fracture Zone (approximately 41°N). Lengths *AA* and *BB* are from Raff (*37*); the length *CC* is equivalent to those shown in Fig. 16. The lower section is taken from the contour maps of Vacquier *et al.* (*50*) and Raff and Mason (*27*). The profile has been calibrated with a possible time scale from the crest of Gorda Ridge out to the boundary of the East Pacific Rise at 168°W.



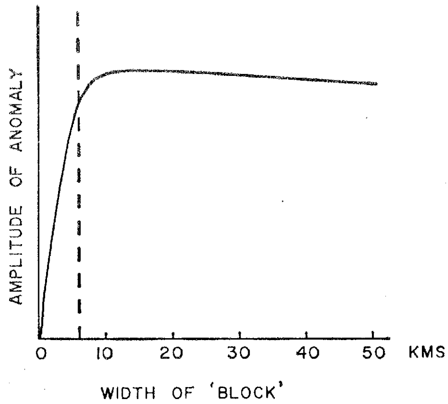


Fig. 18. A schematic diagram illustrating the way in which the amplitude of the anomaly, associated with a "block" of oceanic crust of a particular polarity, is considerably reduced if the width of the block is less than 5 or 6 kilometers.

this fact may well be recorded in the form of marine transgressions or basic igneous intrusions on the present-day continental margins (*40*). By use of these criteria the main part of the Mid-Atlantic Ridge is perhaps 150 to 200 million years old; the northwest Indian Ocean Ridge, 80 to 100 million years old. These ages are compatible with the rates of spreading that I have deduced at the centers of these ridges—approximately 1.5 centimeters per annum.

Of the three points originally unexplained by the Vine-Matthews hypothesis, two have been answered; the remaining difficulty concerns the change in character of the anomalies as one moves from the axial zone of a ridge to the flanks. This change to higher-amplitude and longer-wavelength anomalies is often rather abrupt (*15*). If the Vine and Matthews hypothesis is applicable beyond the central, axial zones of ridges, this change in character may reflect a change in the intensity or frequency, or both, of reversals of Earth's magnetic field. If the frequency of reversals is high, the resulting "blocks" of material of a particular polarity will be narrow; their width will depend on the rate of spreading, but if they are a few kilometers in width they will give rise to a considerably reduced anomaly (Fig. 18). Narrower blocks may well have no obvious individual expression in the magnetic anomaly but will tend to lower the bulk resultant magnetization of the surrounding block. Thus this boundary between the flank and axial-zone anomalies may reflect an increase in the frequency of reversals of Earth's field, together possibly with a decrease in its intensity.

Clearly, if this is the case, the boundary should occur at different distances from ridge axes according to the average rate of spreading in that region. A preliminary investigation of many ridge profiles suggests that this change may have occurred approximately 25 million years ago. Changes in the frequency of reversal seem quite probable when one bears in mind that for the whole of the Permian and part of the Upper Carboniferous the field appears to have been of a single polarity (*41*).

The fact that Vacquier (*12*) was unable to correlate axial-zone anomalies on profiles in the equatorial Atlantic is considered to result partly from this difference in character. Moreover, the model for this latitude and orientation would predict zero or near-zero anomalies, so that one is recording only background noise caused by topography and second-order magnetic contrasts within the crust.

The concept of transform faults (*30*) very neatly explains many oceanic fracture zones, especially in the Atlantic and Indian oceans. There the faults appear to accommodate changes in direction of the ridge crest in splitting the continents, and parts of these oceans are probably riddled with minor transform fractures that obscure the magnetic symmetry on any random profile. In the northeast Pacific, however, the fractures seem to be rather different in character and are often not very obviously accommodating to a general change in direction of the ridge crest (Fig. 15). It seems essential to assume ocean-floor spreading to explain the large offsets on these fractures at all, but within this framework there seem to be two possibilities: transform faults, or a different velocity of spreading on either side of the fracture zone (*3*). By matching anomalies across the fractures one will be able to distinguish between these two possibilities, according to whether the offset remains constant or changes along the length of the fault. As yet no evidence indicates pronounced differential spreading.

Finally, the Vine and Matthews hypothesis may provide the best criterion for distinguishing between active and inactive ridges. Ridges that have actively spread during the last 1 million years should be characterized by a central magnetic anomaly of appropriate sign and shape. Investigation of approximately 100 available crossings of the worldwide ridge system indicates good agreement between observed and predicted anomalies, two sectors excepted (*42*). Magnetic profiles across the Labrador Sea (*43*) show a certain possible symmetry about the center but do not reveal a central anomaly (Fig. 19). If actively spreading, this ridge should be characterized by a very pronounced central anomaly because of the high latitude (compare Fig. 5); this lack of central anomaly fits well with the concept of an extinct and buried ridge, as was revealed by the reflection seismic data (*44*), although occasional shallow-focus earthquakes indicate some residual activity.

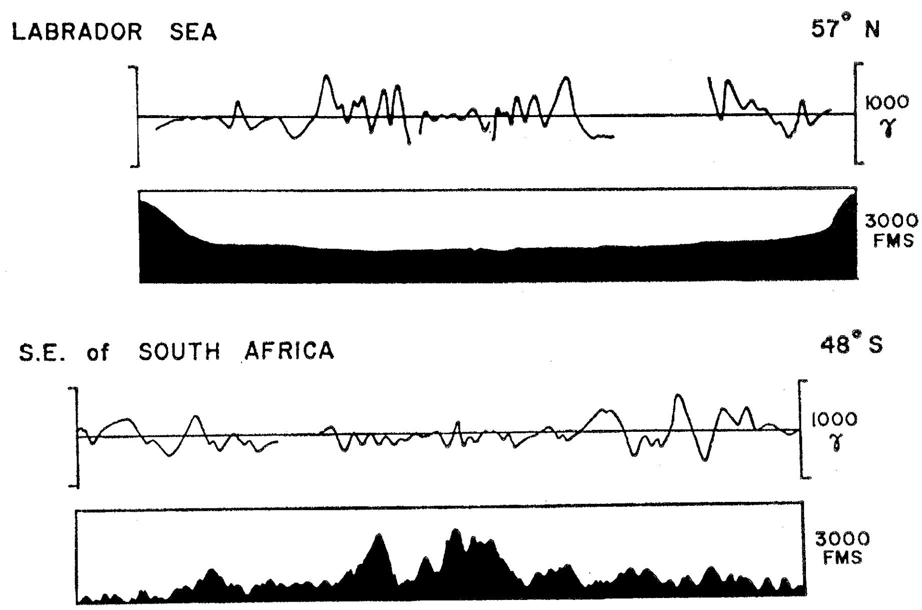


Fig. 19. Observed magnetic profiles and bathymetry recorded by *Vema* across the Labrador Sea and to the southeast of South Africa (*51*). Note the absence of a central magnetic anomaly in each case.

The second area is the ridge system to the southeast of South Africa (Fig. 19); it appears that the central anomaly is consistently absent, although more data are required for confirmation. It is further suggested that, with the exception of Prince Edward Island Rise, the depths in this area are not typical of a mature oceanic ridge. Such mountainous bathymetry and seismic activity as there is can probably be attributed to transverse fractures and residual shearing and igneous activity.

If this observation is significant and the ridge systems in these areas are not actively spreading, the active part of the ridge system at present appears to form two isolated lengths, each traversing half the circumference of Earth: one extends from the Red Sea and the Gulf of Aden, south of Australia, and across the east Pacific to the Gulf of California; the other, down the whole length of the Atlantic. This concept contrasts with the continuous nature of the worldwide ridge system stressed by most authors, but fits well with the "tennis ball" pattern of convection within the upper mantle (*3*), in which the seam of the ball should approximate down currents and compressional features on Earth's surface.

Summary

It is suggested that the entire history of the ocean basins, in terms of ocean-floor spreading, is contained frozen in the oceanic crust. Variations in the intensity and polarity of Earth's magnetic field are considered to be recorded in the remanent magnetism of the igneous rocks as they solidified and cooled through the Curie temperature at the crest of an oceanic ridge, and subsequently spread away from it at a steady rate. The hypothesis is supported by the extreme linearity and continuity of oceanic magnetic anomalies and their symmetry about the axes of ridges.

If the proposed reversal time scale for the last 4 million years is combined with the model, computed anomaly profiles show remarkably good agreement with those observed, and one can deduce rates of spreading for all active parts of the midoceanic ridge system for which magnetic profiles or surveys are available. The rates obtained are in exact agreement with those needed to account for continental drift.

An exceptionally high rate of spreading (approximately 4.5 cm/year) in the South Pacific enables one to deduce by extrapolation considerable details of the reversal time scale back to 11.5 million years ago. Again, this scale can be applied to other parts of the ridge system. Thus one is led to the suggestion that the crest of the East Pacific Rise in the northeast Pacific has been overridden and modified by the westward drift of North America, with the production of the anomalous width and unique features of the American cordillera in the western United States. The oceanic magnetic anomalies also indicate that there was a change in direction of crustal spreading in this region during Pliocene time from east–west to southeast–northwest.

A profile from the crest to the boundary of the East Pacific Rise, and the difference between axial-zone and flank anomalies over ridges, suggest increase in the frequency of reversal of Earth's magnetic field, together, possibly, with decrease in its intensity, approximately 25 million years ago.

Within the framework of ocean-floor spreading, it is suggested that magnetic anomalies may indicate the nature of oceanic fracture zones and distinguish the parts of the ridge system that are actively spreading. Thus data derived during the past year lend remarkable support to the hypothesis that magnetic anomalies may reveal the history of the ocean basins.

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