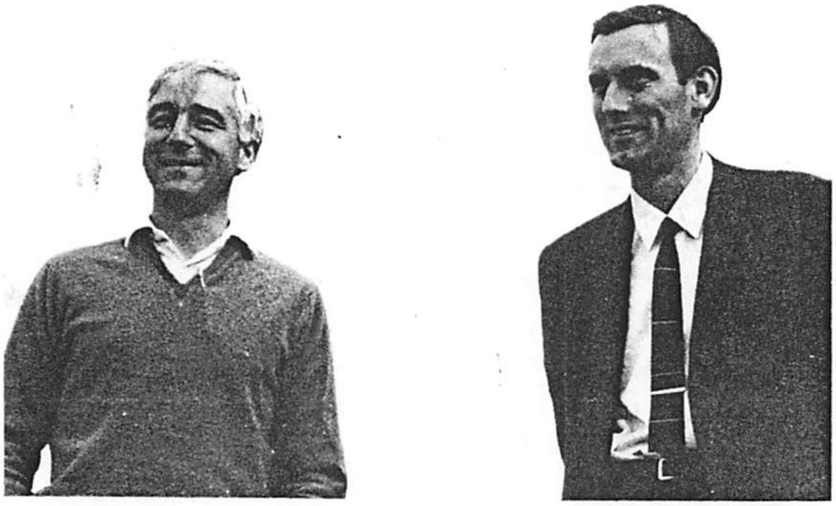

Figure 21-1
Drummond Matthews (left) and Fred Vine

The Birth of a Theory

When scientists look at data that have a pattern as regular and simple as that of the magnetic stripes, they usually get a gut feeling that there must be a simple explanation. In 1963 Frederick Vine and Drummond Matthews provided the simple explanation. They did this (Chapter 22) by combining Hess's theory about sea-floor spreading with the research then being done on the time scale for geomagnetic reversals.

In 1961 Drummond Matthews had completed his Ph.D. research on dredged basalts from the northeast Atlantic ocean. This had convinced him that the mid-Atlantic ridge must be volcanic. Fred Vine, during his undergraduate studies at Cambridge, became convinced that continental drift had occurred and felt that some of the crucial evidence for drift would somehow be found in the study of marine geology and geophysics. In 1962 Vine became a graduate student with the oceanography group of Edward Bullard and Maurice Hill at Cambridge. Together with other members of the group, including Matthews, who had now joined the staff, Vine sailed to the Indian Ocean in 1962 to help make magnetic surveys of the Carlsberg Ridge as part of the International Indian Ocean Expedition. On returning, Matthews became Vine's research supervisor and the two young scientists shared a room in the old stables at Cambridge. They spent many hours reading Hess's paper (Chapter 4) and discussing the volcanic nature of the sea floor. They also began interpreting the magnetic results from the Indian Ocean. In doing computer modeling to fit the anomalies, they realized that the central part of the ridge was normally magnetized, whereas seamounts on the

Magnetic Anomalies over Oceanic Ridges

FRED J. VINE
DRUMMOND H. MATTHEWS
1963

Typical profiles showing bathymetry and the associated total magnetic field anomaly observed on crossing the North Atlantic and North-West Indian Oceans are shown in Fig. 22-1. They illustrate the essential features of magnetic anomalies over the oceanic ridges: (1) long-period anomalies over the exposed or buried foothills of the ridge; (2) shorter-period anomalies over the rugged flanks of the ridge; (3) a pronounced central anomaly associated with the median valley. This pattern has now been observed in the North Atlantic (Heezen et al., 1953; Keen, 1963), the Antarctic (Adams and Cristoffel, 1962), and the Indian Oceans (Heirtzler, 1961; Matthews et al., 1963). In this article we describe an attempt to account for it.

The general increase in wave-length of the anomalies away from the crest of the ridge is almost certainly associated with the increase in depth to the magnetic crustal material (Heezen et al., 1953). Local anomalies of short-period may often be correlated with bathymetry, and explained in terms of reasonable susceptibility contrasts and crustal configurations; but the long-period anomalies of category (1) are not so readily explained. The central anomaly can be reproduced if it is assumed that a block of material very strongly magnetized in the present direction of the Earth's field underlies the median valley and produces a positive susceptibility contrast with the adjacent crust. It is not clear, however, why this considerable susceptibility contrast should exist beneath the median valley but not elsewhere under the ridge. Recent work in this Department has suggest a new mechanism.

In November 1962, H.M.S. *Owen* made a detailed magnetic survey over a central part of the Carlsberg Ridge as part of the International Indian Ocean Expedition. The area (50 × 40 nautical miles; centred on 5° 25′ N., 61° 45′ E.) is predominantly mountainous, depths ranging from 900 to 2,200 fathoms, and the

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V + M 1963

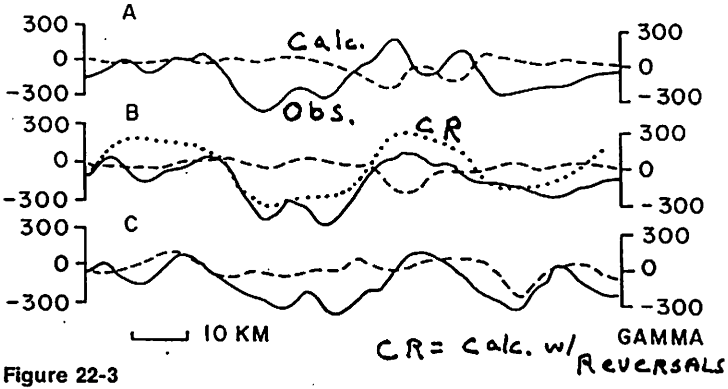

Figure 22-3
Observed and computed profiles across the crest of the Carlsberg Ridge. Solid lines, observed anomaly; broken lines, computed profile assuming uniform normal magnetization and an effective susceptibility of 0.0133; dotted line, assuming reversals—see text. The computed profiles were obtained assuming infinite lateral extent of the bathymetric profiles

The blocks were given the effective susceptibility values shown in the caption to Fig. 22-4(3).

Work on this survey led us to suggest that some 50 per cent of the oceanic crust might be reversely magnetized and this in turn has suggested a new model to account for the pattern of magnetic anomalies over the ridges.

The theory is consistent with, in fact virtually a corollary of, current ideas on ocean floor spreading (Dietz, 1961) and periodic reversals in the Earth's magnetic field (Cox et al., 1963a). If the main crustal layer (seismic layer 3) of the oceanic crust is formed over a convective up-current in the mantle at the centre of an oceanic ridge, it will be magnetized in the current direction of the Earth's field. Assuming impermanence of the ocean floor, the whole of the oceanic crust is comparatively young, probably not older than 150 million years, and the thermo-remanent component of its magnetization is therefore either essentially normal, or reversed with respect to the present field of the Earth. Thus, if spreading of the ocean floor occurs, blocks of alternately normal and reversely magnetized material would drift away from the centre of the ridge and parallel to the crest of it.

This configuration of magnetic material could explain the lineation or 'grain' of magnetic anomalies observed over the Eastern Pacific to the west of North America (Hill, 1963) (probably equivalent to the long-period anomalies of category (1)). Here north-south highs and lows of varying width, usually of the order of 20 km, are bounded by steep gradients. The amplitude and form of these anomalies have been reproduced by Mason (Mason, 1958; Mason and Raff, 1961), but the most plausible of the models used involved very severe restrictions on the distribution of lava flows in crustal layer 2. They are readily explained in terms of reversals assuming the model shown in Fig. 22-4 (1). It can be shown that this type of anomaly pattern will be produced for virtually all orientations and magnetic latitudes, the amplitude decreasing as the trend of the ridge approaches north-south or the profile approaches the magnetic equator. The pronounced central anomaly over the ridges is also readily explained in terms of reversals. The central block, being most recent, is the only one which has a uniformly directed magnetic vector. This is comparable to the area of normally magnetized late Quaternary basics in Central Iceland (Hospers, 1954; Thorarinsson et al., 1959-1960) on the line of the Mid-Atlantic Ridge. Adjacent and all other blocks have doubtless been subjected to subsequent vulcanism in the form of volcanoes, fissure eruptions, and lava flows, often oppositely magnetized and hence reducing the effective susceptibility of the block, whether initially normal or reversed. The effect of assuming a

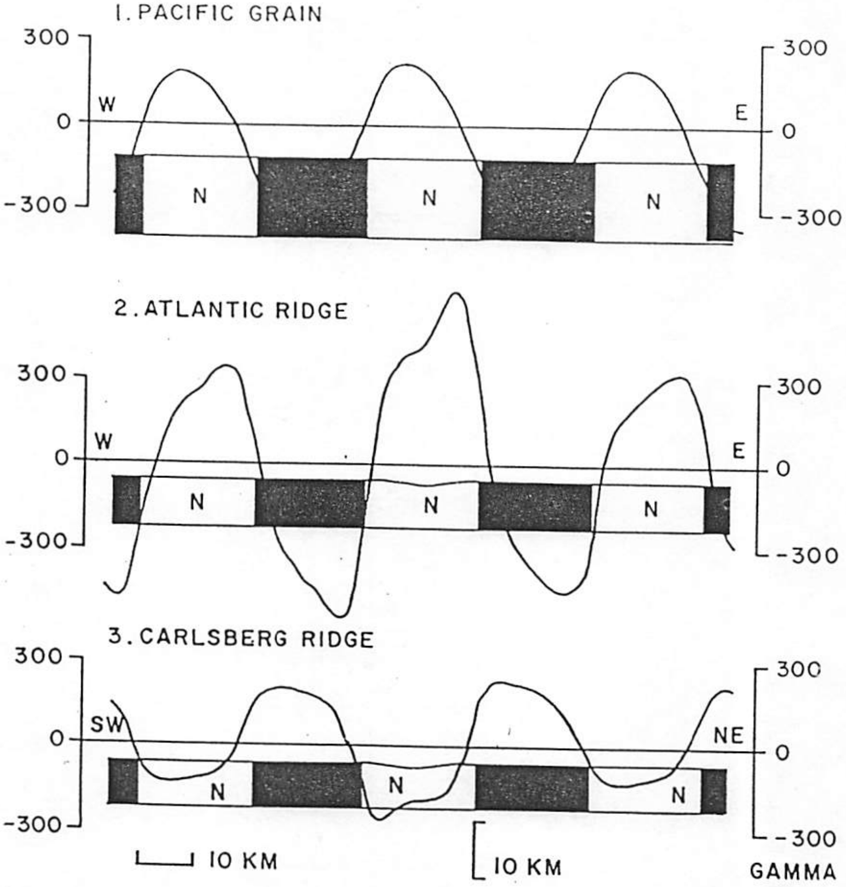

Figure 22-4
Magnetic profiles computed for various crustal models. Crustal blocks marked N, normally magnetized; diagonally shaded blocks, reversely magnetized. Effective susceptibility of blocks, 0.0027, except for the block under the median valley in profiles 2 and 3, 0.0053. (1) Pacific Grain. Total field strength, $T = 0.5$ oersted; inclination, $I = 60°$; magnetic bearing of profile, $\theta = 073°$. (2) Mid-Atlantic Ridge, $T = 0.48$ oersted; $I = 65°$; $\theta = 120°$. (3) Carlsberg Ridge, $T = 0.376$ oersted; $I = -6°$; $\theta = 044°$

reduced effective susceptibility for the adjacent blocks is illustrated for the North Atlantic and Carlsberg Ridges in Fig. 22–4(2,3).

In Fig. 22–4, no attempt has been made to reproduce observed profiles in detail, the computations simply show that the essential form of the anomalies is readily achieved. The whole of the magnetic material of the oceanic crust is probably of basic igneous composition; however, variations in its intensity of magnetization and in the topography and direction of magnetization of surface extrusives could account for the complexity of the observed profiles. The results from the preliminary Mohole drilling (Cox and Doell, 1962; Raff, 1963) are considered to substantiate this conception. The drill penetrated 40 ft. into a basalt lava flow at the bottom of the hole, and this proved to be reversely magnetized (Cox and Doell, 1962). Since the only reasonable explantion of the magnetic anomalies mapped near the site of the drilling is that the area is underlain by a block of normally magnetized crustal material (Raff, 1963), it appears that the drill penetrated a layer of reversely magnetized lava overlying a normally magnetized block.

23

Magnetic Anomalies over A Young Oceanic Ridge off Vancouver Island

FRED J. VINE
J. TUZO WILSON
1965

Surveys of the earth's total magnetic field have been made along closely spaced lines over large areas in the northeastern Pacific Ocean. (Mason, 1958; Vacquier et al., 1961; Mason and Raff, 1961; Raff and Mason, 1961; Peter and Stewart, 1965). These show a surprisingly regular, linear pattern of anomalies, often hundreds of kilometers long and tens of kilometers wide, and usually aligned approximately north-south. Vine and Matthews (1963) have suggested that these anomalies, together with the central magnetic anomaly observed over certain oceanic ridges, might be explained in terms of ocean-floor spreading (Holmes, 1929; Hess, 1962) and periodic reversals of the earth's mgnetic field. The idea proposes that as new oceanic crust is formed over a convective upcurrent in the mantle, at the center of an oceanic ridge, it will be magnetized in the ambient direction of the earth's magnetic field. If the earth's field reverses periodically as ocean-floor spreading occurs, then successive strips of crust paralleling the crest of the ridge will be alternately normally and reversely magnetized, thus producing the linear anomalies of the northeastern Pacific. These anomalies are not obviously parallel to any active oceanic ridge, but it seems possible that they are related in this way either to the East Pacific Rise, as suggested by Menard (1964), or to the extinct Darwin Rise, as suggested recently by Hess (1965).

At the time it was put forward, the Vine and Matthews hypothesis was particularly speculative in that no large-scale magnetic survey was thought to be available for an oceanic ridge, and results regarding the periodicity, or even confirmation, of possible reversals of the earth's magnetic field were very preliminary (Cox et al., 1963a). Recently the evidence suggesting possible reversals of the earth's field has been examined more critically and a periodicity suggested for the past 4 million years (Cox et al., 1964b). Furthermore, it has been

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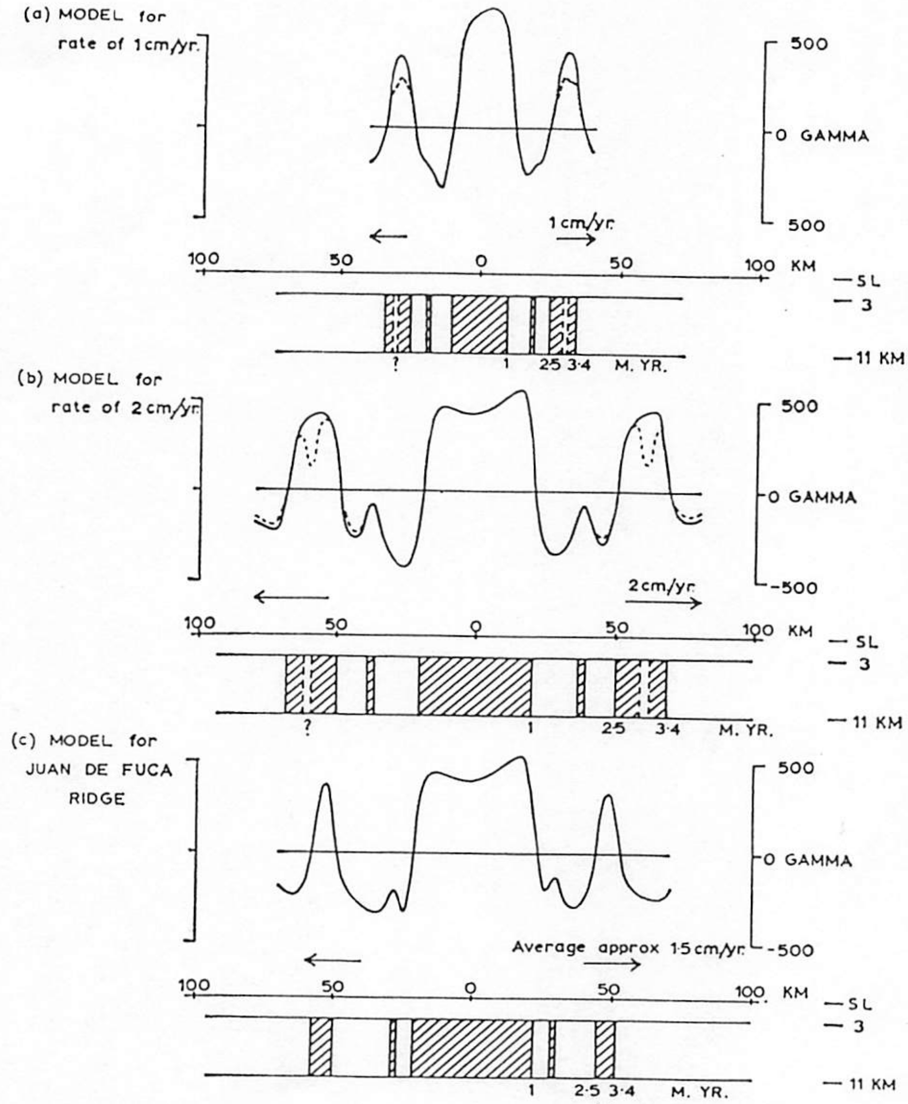

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Figure 23-1
Models and calculated total field magnetic anomalies resulting from a combination of suggested recent polarities for the earth's magnetic field (Cox et al., 1964) and ocean floor spreading. Normally magnetized blocks are shaded; reversely magnetized blocks unshaded. Portions (a) and (b) assume uniform rates of spreading. Portion (c) was deduced from the gradients on the map of observed anomalies. The dashed parts of the computed profiles show the effect of including the possible reversal at 3 million years (Cox et al., 1964) (see footnote 1, page 239)

idea that the steep magnetic gradients so obvious from any detailed magnetic survey over the oceans might delineate the boundaries between essentially normally and essentially reversely magnetized crust, thus reproducing the observed gradients without recourse to improbable structures or lateral changes in petrology. If this basic principle is accepted, there is no difficulty in explaining the anomalies but only in deciding on the distribution of magnetization within the various layers of the oceanic crust (Cann and Vine, 1966). As ever in the interpretation of magnetic anomalies, there is no unique solution, and the various

* Note that they call the Olduvai event, the Gauss normal epoch ⇒ erratic spreading rate!.

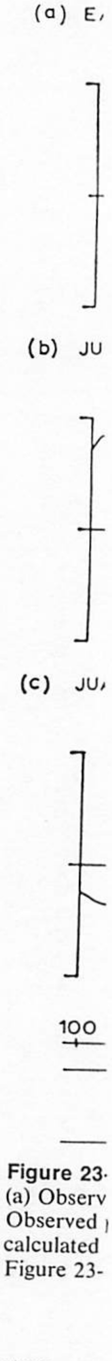

Figure 23
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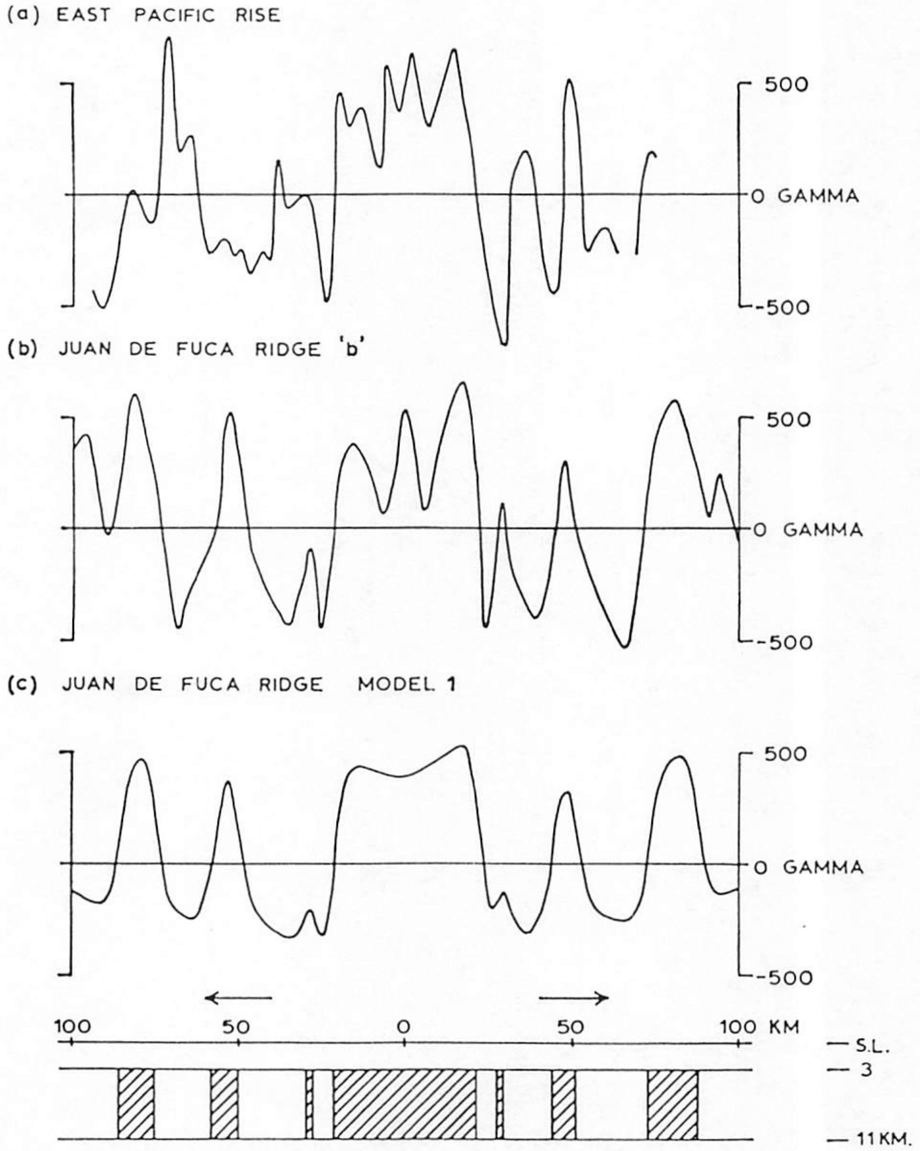

Figure 23-2
(a) Observed profile across the East Pacific Rise at 59°S, 149°W (Heirtzler, 1961). (b) Observed profile "b" across the Juan de Fuca Ridge (see Figure 23-4). (c) Model and calculated anomaly for Juan de Fuca Ridge, assuming generalized crustal blocks (compare Figure 23-1,c)

parameters are so "flexible" that, having assumed normal and reverse strips, the model can be fitted to any existing concept of the structure of oceanic ridges.

Ocean-floor spreading implies that the oceanic crust is a surface expression of the mantle; it must therefore be generated from the mantle and be capable of being resorbed by it, as emphasized by Hess (1965). Basalt is the most common outcropping hard rock on the ocean floor; if this is regarded as the lowest melting fraction of the material of the upper mantle then it probably represents only a small percentage of this material by volume. Hess

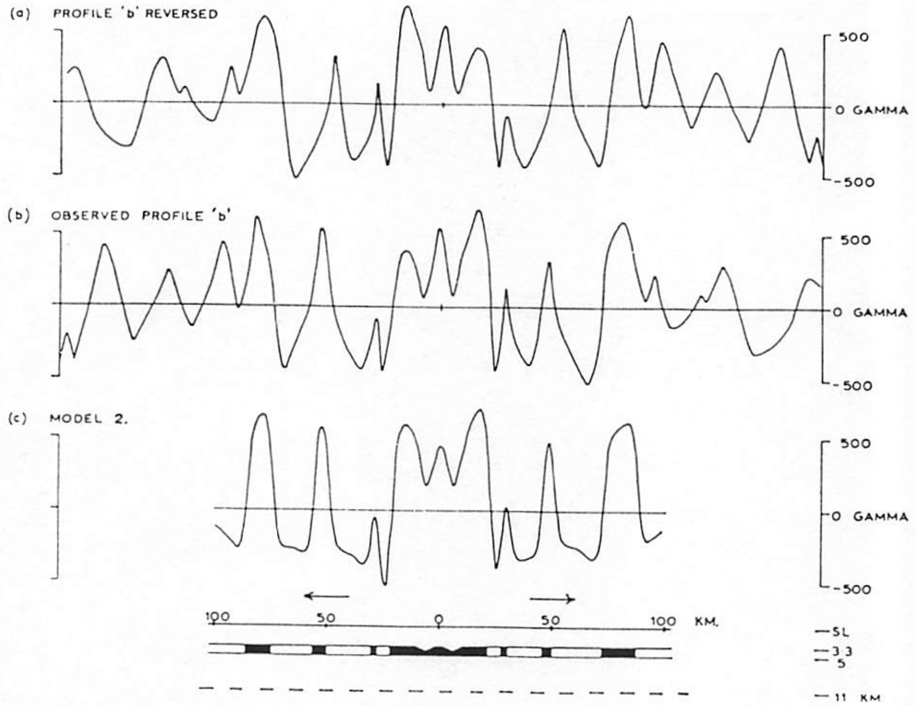

Figure 23-3
(a) and (b) Observed profile "b" across the Juan de Fuca Ridge together with its mirror image about its midpoint, to demonstrate its symmetry. (c) Model and calculated anomaly for Juan de Fuca Ridge assuming a strongly magnetized basalt layer only. Black, normally magnetized material; unshaded material of this layer, reversely magnetized. Normal or reverse magnetization is with respect to an axial dipole vector; axial dipole dip taken at +65°. Effective susceptibility taken as ±0.01, except for the central block, +0.02

considers, therefore, that basalt accounts for only a thin veneer 1 or 2 km thick on top of a main crustal layer of serpentinite, that is, hydrated mantle. The great thickness of basalt lavas in central Iceland (Bodvarsson and Walker, 1964) is clearly anomalous in that the whole crustal section is thicker, and away from the center the volcanics have been subjected to erosion, unlike those of the submarine ridges. Assuming the validity of the model for oceanic ridges proposed by Hess (1965), the "magnetic" material of the crust would be largely confined to the basalt layer (layer 2). Hess envisages that the serpentinite layer (layer 3) is emplaced in the solid state and it would therefore acquire its remanent magnetization at depth on passing through the Curie point isotherm. By the time it is emplaced beneath the central rift it might well be highly sheared, fractured, and randomly orientated. Serpentinite would appear to be weakly magnetized and to have a Konigsberger ratio of approximately 1 (Cox et al., 1964c). All in all it would probably be capable of contributing little to the observed magnetic anomalies. The basalt, however, cools through the Curie point in place in the form of lava flows or intrusives. It is strongly magnetized, and its remanent magnetization probably predominates, since its susceptibility would appear to be comparatively low (Ade-Hall, 1964). In Fig. 23-3,*c* the magnetic anomalies have been computed over a model in which the magnetic material is confined entirely to layer 2. As previously, the central block is assumed to be more strongly magnetized because it is the only block composed exclusively of young material which is magnetized normally, except for the minor possibility of self-reversals. Volcanism probably occurs over a wider zone than the central

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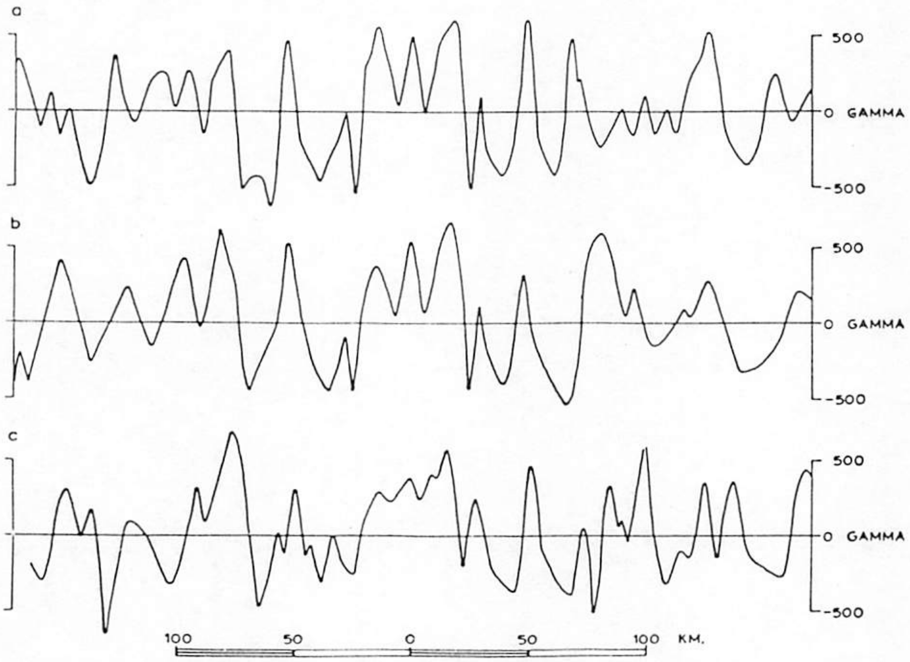

Figure 23-4
Observed profiles (a), (b), and (c) at intervals of 45 km along Juan de Fuca ridge, north to south. Midpoint of profile "b" is 46°39′N. 129°24′W. True bearing of profiles is 110

Shows continuity!

block, and all other blocks will therefore be contaminated with younger material, often of reverse polarity to that of the initial block, and hence lowering or modifying its resultant magnetic effect. The serpentinite of layer 3 is almost certainly riddled with basaltic feeders for the flows and intrusives of layer 2. If these feeders are taken into account they will have the effect of slightly lowering the effective susceptibility assumed for layer 2 in Fig. 23–3,*c*. This susceptibility is, as it stands, comparatively high but not unreasonable.

Comparison of Figs. 23–2,*c* and 23–3,*c* confirms that the essential feature of the Vine and Matthews hypothesis is the normal-reverse contacts; the actual distribution of magnetization within layers 2 and 3 of the oceanic crust is a matter of speculation at the present time (Vine and Matthews, 1963; Cann and Vine, 1966). However, the comparison also suggests that the second model is a considerable improvement on the first, despite the fact that it is still very simple. The original, generalized model of Vine and Matthews (Model 1) and the specific model after Hess (Model 2) have been chosen to illustrate what are possibly the two extremes, but it seems increasingly probable that the observed anomalies can best be reproduced by strongly magnetized, basalt material in layer 2 and less strongly magnetized material at depth, whether this decrease in magnetization be due to a general increase in grain size, a change in rock type, or metamorphic effects.

A literal interpretation of the Vine and Matthews hypothesis implies that the magnetic anomalies observed over ridges at certain latitudes and orientations should be roughly symmetrical (for example, as in Fig. 23–1), but the simplicity of this model when compared with the probable complexity of the real situation makes a high degree of symmetry improbable. Iceland, although atypical in some ways, must give certain pointers as to the nature of the crestal province of the ridge system. Work on Iceland (Bodvarsson and Walker,

24

Spreading of the Ocean Floor: New Evidence

FRED J. VINE

1966

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 (Bullard et al., 1965). 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 (1962), 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 (1965) and Dietz (1966), 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 (1965; 1966) 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 (1965d) 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.

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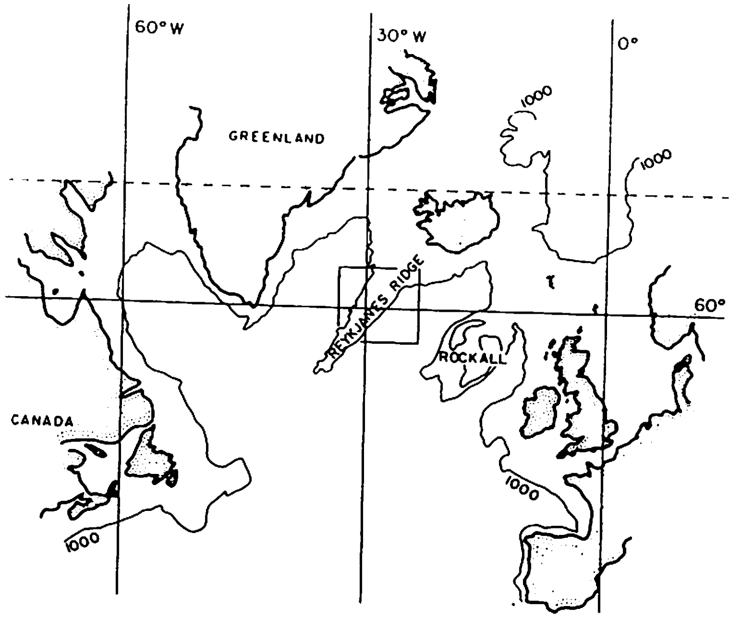

Figure 24-2
The location of Reykjanes Ridge, southwest of Iceland, and the area of Figure 24-3. The 1000-fathom submarine contour is shown, together with the 500-fathom contours for Rockall Bank

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 (1963) and emphasized by Heirtzler and Le Pichon (1965). 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.

COROLLARIES

The second difficultly 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[1] made a detailed aeromagnetic survey of Reykjanes Ridge, southwest of Iceland (Fig. 24-2) (Heirtzler et al., 1966). 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 (Avery, 1963). A diagram summarizing the anomalies revealed by this survey appears in Fig. 24-3. 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. 24-1), recently described by Wilson (1965b), 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

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[1] At the suggestion of Lamont Geological Observatory.

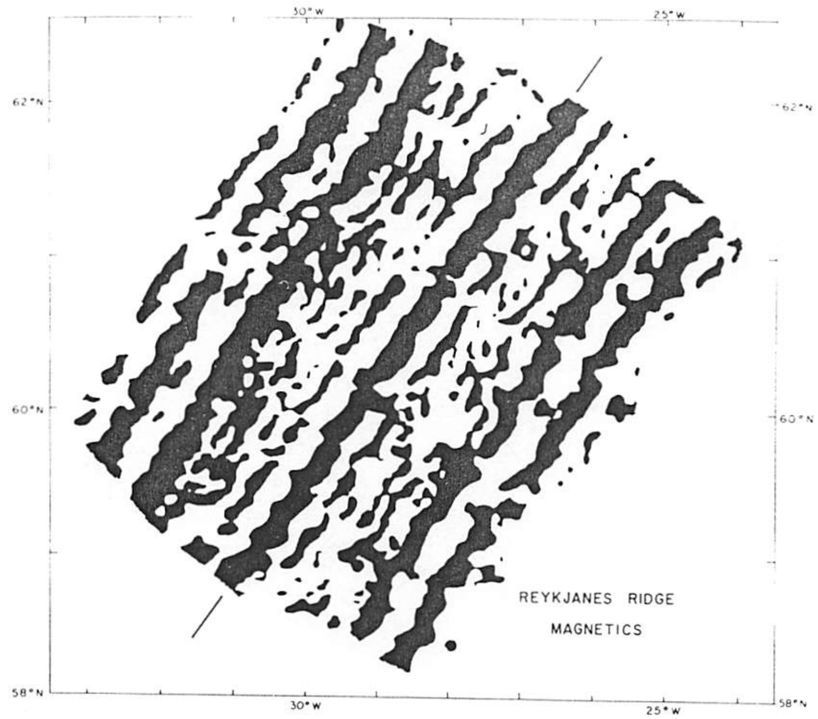

Figure 24-3
Summary diagram of the magnetic anomalies observed over Reykjanes Ridge (see Figure 24-2). Straight lines indicate the axis of the ridge and the central positive anomaly (Heirtzler et al., 1966)

anomalies at ridge crests by assuming the reversal time scale for the last 4 million years proposed by Cox, Doell, and Dalrymple (1964b), the only additional parameter being the rate of spreading; the scale (Fig. 24-4) has recently received striking independent confirmation from the work of Opdyke et al. (1966) on deep-sea sedimentary cores.

REYKJANES RIDGE

Observed anomaly profiles obtained during four crossings of the crest of Reykjanes Ridge are compared (Fig. 24-5) 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 (Vine and Wilson, 1965 – 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.[2] 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. 24-2), is a continental fragment, as was assumed by Bullard, Everett, and Smith

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[2] For the two models in Fig. 24-5 the intensity of Earth's field was taken as 51,600 gamma; its dip, ±74.3°; the magnetic bearing of the profile, 153°. Normal or reverse magnetization is with respect to an axial dipole vector. Effective susceptibility assumed, ±0.01 – except for the central block (+0.02).

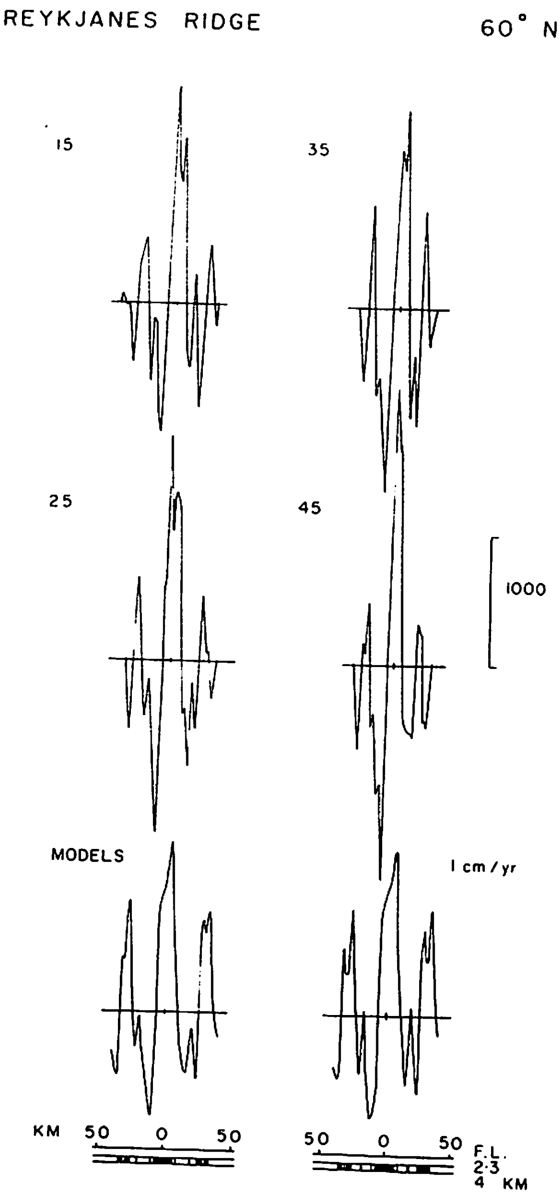

Figure 24-5
Profiles observed across Reykjanes Ridge, together with computed profiles. The model to the left assumes the reversal time scale of Figure 24-4; that to the right, the "revised" time scale of Figures 24-12 and 24-13 (see footnote 2, page 249). All observed and computed profiles have been drawn to the same proportion: 10 kilometers horizontally is equivalent to 100 gamma vertically (1 gamma = 10^{-5} oersted). F.L., flight level

in the rate of spreading, because of the rotation of South America relative to Africa (Bullard et al., 1965) 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 (1965, fig. 3), may well be an expression of this phenomenon.

THE RED SEA

In Fig. 24-10 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 (Girdler, 1962),

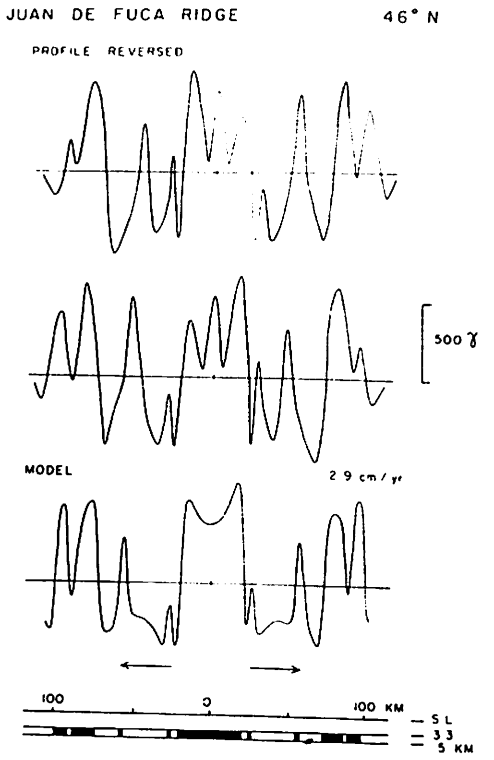

Figure 24-6
Observed magnetic profile over the Juan de Fuca Ridge compared with a simulated profile based on the reversal time scale of Figure 24-4 assuming a constant rate of spreading and the model described in footnote 3, page 250. The observed profile is taken from Raff and Mason (1961). See also Vine and Wilson (1965), Figure 3. S.L., sea level

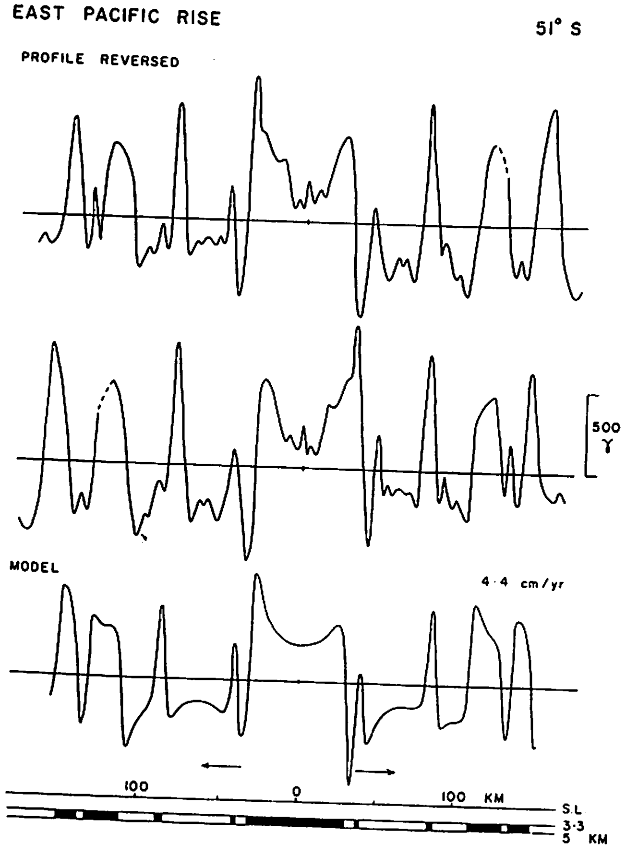

Figure 24-7
Observed magnetic profile over the East Pacific Rise compared with a simulated profile based on the reversal time scale of Figure 24-4 assuming a constant rate of spreading and the model described in footnote 3, page 250. The observed profile is the Eltanin-19 profile of Pitman and Heirtzler (1966). S.L., sea level

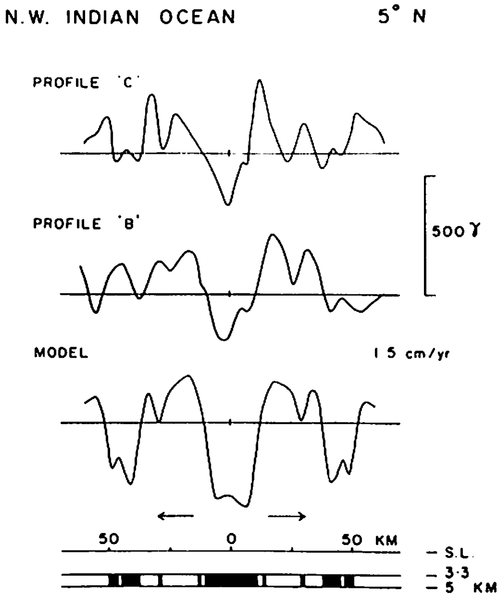

Figure 24-8
Observed magnetic profile over the northwest Indian Ocean compared with a simulated profile based on the reversal time scale of Figure 24-4 assuming a constant rate of spreading and the model described in footnote 3, page 250. The observed profiles are the Owen profiles of Matthews, Vine, and Cann (1965), Figure 2. S.L., sea level

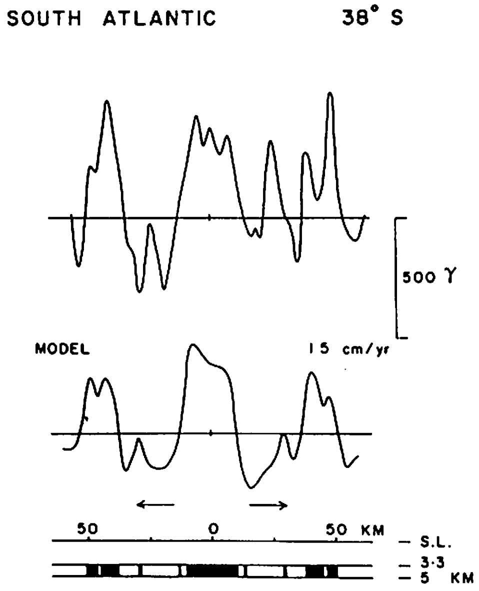

Figure 24-9
Observed magnetic profile over the South Atlantic Ocean compared with a simulated profile based on the reversal time scale of Figure 24-4 assuming a constant rate of spreading and the model described in footnote 3, page 250. The observed profile is taken from Heirtzler and Le Pichon (1965), Figure 1. S.L., sea level

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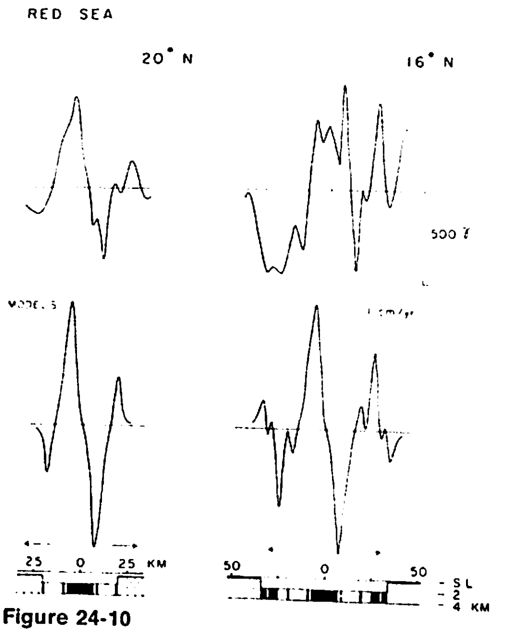

Figure 24-10
Observed profiles across the Red Sea (from Allan et al., 1964; Drake and Girdler, 1961) compared with computed profiles based on a constant rate of spreading and a truncated model and time scale according to the width of the central depression and zone of magnetic anomalies. (See footnote 4, page 254). Stippled area, "nonmagnetic" continental material

then clearly such a simulation should be attempted. However, the depth to this embryonic ocean floor and its crustal section (Drake and Girdler, 1961) are not typical of an oceanic ridge, and this floor almost certainly includes some assimilated or foundered continental material.

In Fig. 24-10 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.[4] 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 (Vine and Wilson, 1965). In Fig. 24-11 boundaries inferred from the observed profiles across the East Pacific Rise and Juan de Fuca and Reykjanes ridges (Figs. 24-5–24-7) are plotted against the reversal time scale of Cox, Doell, and Dalrymple (1964b), 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 (1965).

In this earlier time scale the Jaramillo event (Fig. 24-4) 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. 24-6 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 (Vine and Wilson, 1965).

It will be seen that, had the authors had more faith in the idea and the probability of a

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[4] Parameters assumed for the Red Sea models in Fig. 24-10; intensity and dip of Earth's field, 38,500 gamma and +24° respectively; magnetic bearing of profiles, 054°. Intensity and direction of magnetization as for Fig. 24-5.

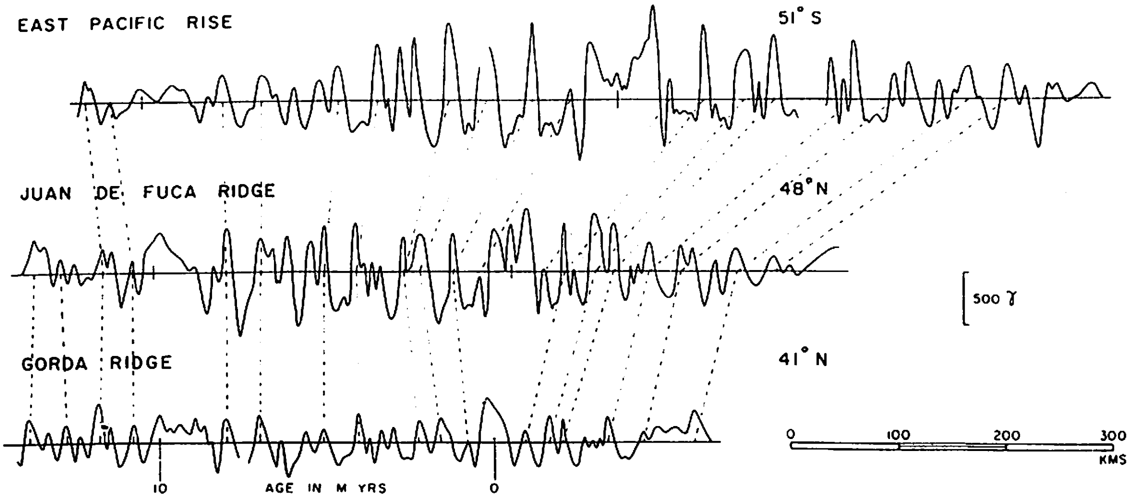

Figure 24-14
The East Pacific Rise profile Eltanin-19 (Pitman and Heirtzler, 1966) compared with a composite profile across and to the northwest of Juan de Fuca Ridge, and with a profile normal to the strike of the anomalies across and to the west of Gorda Ridge. (The last two profiles from Raff and Mason, 1961, and Vacquier et al., 1961)

South of Cape Mendocino, current crustal spreading appears to be accommodated along the San Andreas fault, as was proposed by Wilson (1965c). 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 (Mason and Raff, 1961) (see Fig. 24–15). 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 north of the Mendocino (had it not been stifled) and assumes the offsets measured further west on the Mendocino and Pioneer fractures (Vacquier, 1965), the reconstructed ridge crest lies beneath Utah and Arizona—the area of the Colorado Plateau uplift (see Fig. 24–15).

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 (Rusnak et al., 1964; Laughton, 1966), 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 (Menard, 1966), 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 (Wilson, 1965c) 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 (1964), and a fact perhaps precluding east-west or northeast-southwest compression. I must emphasize that my evidence (essentially contained in Fig. 24–14) 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 (1963) (see Fig. 24–15).

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