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The Bakerian Lecture, 1967: Reversals of the Earth's Magnetic Field

Edward Bullard

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THE BAKERIAN LECTURE, 1967

REVERSALS OF THE EARTH'S MAGNETIC FIELD

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CONTENTS

This paper is an account of the Bakerian Lecture given to the Royal Society on 15 June 1967. Reversals of the Earth's magnetic field can be studied in the magnetization of lavas and sediments on land, in the magnetization of deep sea cores and in the magnetic pattern on the ocean floor. The lavas give radiometric dates but not a continuous sequence; the cores give continuity, great detail and a resolution as fine as 1000 years; the magnetic pattern gives information all through the Tertiary and connects the spreading of the ocean floor with the radiometric time scale.

The dynamo theory of the Earth's magnetic field may be able to account for reversals as an instability in the dynamo, but only models with a finite number of degrees of freedom have been investigated. Spreading of the ocean floor is believed to be associated with convective motions in the upper mantle, although there are difficulties connected with the equality of the oceanic and continental heat flows.

There is some evidence for the extinction of radiolaria at times of reversal of the magnetic field; it has been suggested that this is due to the effect of the field on cosmic rays but this appears impossible. If the extinctions are due to the reversals, the mechanism is unknown.

Reversely magnetized rocks are more highly oxidized than normally magnetized ones. The cause of this is unknown and is one of the outstanding problems of Earth science.

1. INTRODUCTION

Sixty years ago, Brunhes (1906) showed that some rocks are magnetized in a direction rather accurately opposite to that of the present magnetic field of the Earth. This striking phenomenon was almost totally neglected for 40 years (but see the references given by Koenigsberger (1938), especially Mercanton (1910), Matuyama (1929) and Gelletich (1937)) and it is only very recently that it has been realized that these reversals of magnetization are connected with many of the fundamental problems of earth science. The purpose of this lecture is to review these developments in both their geological and their physical aspects.

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2. Reversed and normally magnetized rocks

Objects that have been baked by man, such as bricks, pottery and kilns, are invariably magnetized in the direction of the field at the time of the baking; deviations from the direction of the present field are due mainly to the secular variation of the field and enable that variation to be investigated both in magnitude and direction for periods before the first instrumental measurements, which go back only to the sixteenth century (Bucha 1967; Chevalier 1925; Thellier & Thellier 1959). Similar results are obtained from Recent and Pleistocene lavas (with rare exceptions, which will be discussed in §3). The explanation of these facts is very simple: when any ferromagnetic material with randomly oriented crystals is heated above its Curie point and cooled in a magnetic field, it becomes magnetized in the direction of the field. If the susceptibility is not too great, the field within the body is in almost the same direction as the applied field and is independent of the shape of the body; this condition is satisfied for igneous rocks whose susceptibility is typically of the order of 10^{-3}. Similar phenomena occur with sediments. Here there may be more than one process of magnetization. As ferromagnetic grains sink in water they may be in some degree oriented by the magnetic field, giving a nett magnetization in the direction of the field. Another process which is less well understood is the magnetization of chemical compounds formed in a magnetic field; in particular it seems that if sand grains are coated with iron oxides the coating becomes magnetized as it is formed, or perhaps as it is oxidized.

3. Reversals in lavas

On examining older rocks a new phenomenon is found: for Tertiary rocks, that is rocks formed between 1 and 70 million years before the present, about half are found to be reversely magnetized. If ten or twenty samples are taken covering a time span of 1000 years or more and the directions of magnetization are averaged, the effects of secular variation are largely eliminated and the mean approximates to the geographical north or south direction with the accuracy to be expected from the scatter of the individual measurements. Older, pre-Tertiary, rocks show directions of magnetization that depart from the present north and south directions; such departures are the result of polar wandering and continental drift and will not be further considered here. They do not obscure the existence of two opposite directions of magnetization and from the continuity of the motions of the continents it is usually possible to say which is the normal and which the reversed direction.

Irving (1964) has collected all measurements of the direction of magnetization up to 1963. Table 1 gives the number of his rock groups in each geological period that give normal (N) and reversed (R) polarity and also the number (M) giving sometimes one and sometimes the other polarity. A rock group usually includes many specimens taken from several sites; its formation often covered a period of several million years as, for example, did the Old Red Sandstone of England. In the light of the discussion later in this paper the occurrence of 'mixed' polarities is certainly due to this coarseness of the sampling and also, perhaps, to a proportion of unreliable results. In table 2 the results are combined in larger groups to allow a more reliable assessment of the proportion of normal and reversed rocks. The Quaternary results have been omitted from this table to avoid combining a large number of results from so short a period with the other more or less comparable groups.

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The last column of table 2 gives the probability of finding a deviation from equal numbers as great as that observed if the results are a random sample drawn from a population in which the two polarities are equally probable.

Table 1. Numbers of rock units in each geological period having normal (N), reversed (R) and mixed (M) polarities

period	time interval (My)	numbers N	R	M
Precambrian	> 600	49	23	16
Cambrian	600–500	7	15	5
Ordovician	500–425	5	2	3
Silurian	425–405	7	4	3
Devonian	405–345	12	16	22
Carboniferous	345–280	24	34	15
Permian	280–230	2	50	8
Trias	180–230	21	9	17
Jurassic	135–180	37	5	12
Cretaceous	63–135	13	3	3
Tertiary	63– 2	37	42	43
Quaternary	2– 0	51	5	11

Table 2. Results from table 1 combined

	N	R	N/R	probability
Precambrian	49	23	2·1	0·0015
Cambrian to Devonian	31	37	0·84	0·27
Carboniferous	24	34	0·70	0·12
Permian	2	50	0·02	3×10^{-13}
Trias to Cretaceous	71	17	4·2	3×10^{-9}
Tertiary	37	42	0·88	0·33
total	214	203	1·1	0·31

It is clear that the total numbers of reversed and normal rocks are about equal and that this is also true of the Palaeozoic (without the Permian) and of the Tertiary. All but two of the Permian rocks are reversed and the bulk of Mesozoic ones are normal. The pre-Cambrian shows an excess of normal magnetization but there may well be doubt about many of these ancient specimens. The uniformity of the reversal in the Permian is very striking; one of the two exceptions is from the Pyrenees and is a sediment which may be Triassic and may have acquired its magnetization in the Tertiary; contemporary igneous rocks from the same area are reversely magnetized. The other normally magnetized Permian rock is from Szechwan, the results for it have a large scatter but show no other sign of unreliability.

The central problem is to discover whether the reversals of magnetization are due to reversals of the field in the past or to some chemical or mineralogical peculiarity of the rocks.

In 1951 it was discovered that a lava, a dacite from the volcano of Haruna in Japan, became magnetized in a direction opposite to the ambient field when it was cooled from a temperature above its Curie point (Nagata 1951, 1961; Nagata, Uyeda & Akimoto 1952). A number of mechanisms that would explain this bizarre behaviour were suggested by Néel (1951) and Uyeda (1958). For a while it seemed quite uncertain whether all, or most,

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of the reversely magnetized rocks found in nature had behaved in this way or were indicators of field reversals in the past (Blackett 1962). The ensuing controversy brought out a number of lines of evidence suggesting that field reversals were almost always the cause of reversed magnetization. First, self-reversing rocks have proved extremely rare; in fact the only example, other than the Haruna dacite, is a basalt dredged from the Pacific (Ozima & Ozima 1967), this acquires a reversed polarity only when heated for less than 150 mins to a temperature between 300 and 330 °C; other temperatures or longer heating show no reversal. Self-reversing mineral grains can be separated from some rocks (Uyeda 1958) and other rocks can be rendered self-reversing by suitable heat treatment (Carmichael 1961; Everitt 1962).

The universal normal magnetization of recent and Pleistocene rocks, except for the Haruna dacite, also speaks strongly against spontaneous self-reversal as a common process. Perhaps the most convincing of the early arguments was the observation that, when a lava or an intrusive rock has baked another lava or a sediment, the baked rock invariably has the same direction of magnetization as the baking rock; over one hundred examples are known (Wilson 1962*a*, *b*, 1966) and it would be very difficult to explain this except by supposing that the magnetization represents the direction of the Earth's field at the time of the baking. Other arguments are given by Wilson & Haggerty (1966).

These arguments were strong but did not seem conclusive to all. What was required was a study of the distribution of normal and reversed magnetization in time and space. If all rocks formed during certain periods have a normal polarity and all rocks formed during other periods have a reversed polarity, then the cause can hardly be other than a reversal of the Earth's field; it is inconceivable that there can be world-wide periods when the chemistry of all rocks, igneous and sedimentary, changes in such a way that they become spontaneously reversing. The great preponderance of reversely magnetized rocks during the Permian suggests that there are, in fact, world-wide periods of one polarity. It is, however, important to look more closely and to examine periods when there are both reversely and normally magnetized rocks.

In the 1950s many workers (for example, Hospers 1951, 1953*a*, *b*, 1954; Khramov 1957; Creer 1958; Girdler 1959) found evidence of reversals at intervals of a few hundred thousand years in Tertiary and Mesozoic rocks, but the dating of the rocks was not sufficiently accurate to show that the changes of polarity were simultaneous in widely separated places. The ages of lavas are nearly always determined by the potassium–argon method. Since the ages have an uncertainty of, at best, 3%, it is desirable to investigate lavas not more than 4 My old; for older rocks the uncertainty in the ages may make it impossible to correlate reversals between different regions (Cox & Dalrymple 1967*a*; Dalrymple, Cox, Doell & Grommé 1967).

The first studies of lavas in which both the polarities and the ages were determined with adequate precision on carefully chosen material, were those of Cox, Doell & Dalrymple (1963*a*, *b*) and McDougall & Tarling (1963). The results strongly suggest a consistent pattern of ages which has been confirmed and extended by later work (Grommé & Hay 1963; Cox, Doell & Dalrymple 1964*a*, *b*, 1965; McDougall & Tarling 1964; Dalrymple, Cox & Doell 1965; Chamalaun & McDougall 1966; Cox & Dalrymple 1966, 1967*a*, *b*; Cox, Hopkins & Dalrymple 1966; Doell & Dalrymple 1966; Doell, Dalrymple & Cox 1966; McDougall

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& Wensink 1966; Cox, Dalrymple & Doell 1967; Ozima *et al.* 1967). For both the magnetic and the age determinations it is desirable to set strict requirements for the specimens; many lavas have suffered chemical changes after solidifying and may have lost argon, some contain overwhelming amounts of atmospheric argon, some may not have been free from argon when formed, some are magnetically unstable, some are magnetized by lightning and a few are spontaneously reversing. Criteria have been set out by Cox *et al.* (1963 *b*), Doell *et al.* (1966) and Cox *et al.* (1966). One hundred and twenty-one of the most reliable results are given in figure 1; each point represents a number of concordant samples from one or more lava flows. During the last 3·6 My there have been four main periods of alternating normal and reversed magnetization which have been named the Brunhes, Matuyama, Gauss and Gilbert epochs. There are also three shorter periods called the Jaramillo, Olduvai and Mammoth events after the places where they were first found. It will be seen from figure 1

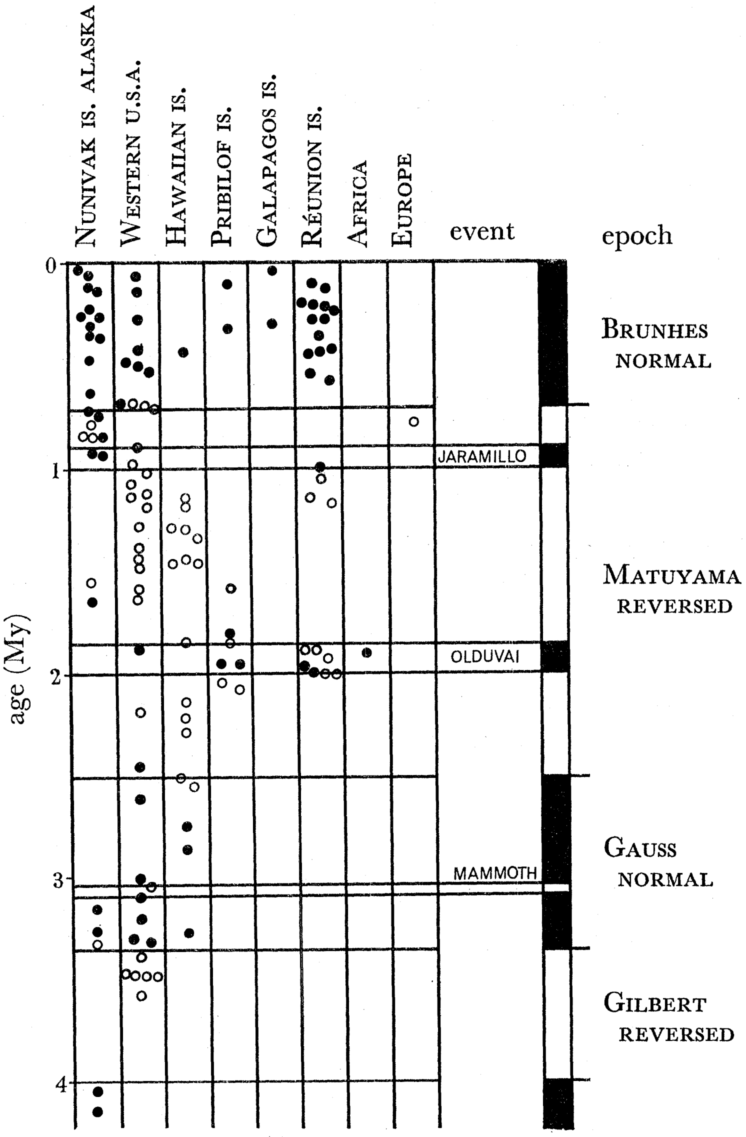

Figure 1. Ages and direction of magnetization of lavas (adapted from Opdyke & Foster 1967). A specimen from Nunivac Island which may represent the doubtful Gilsa event is shown at 1·65 My.

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that the reality of the first two of these brief events is quite well established by samples from several parts of the world. Naturally the uncertainty in the ages causes rocks of both polarities to be intermixed for 100 ky or so on either side of a boundary between a normally and a reversely magnetized period; however the epochs, which last for about a million years, are clearly demarcated. The events are only 100 or 200 ky in duration and therefore are not clearly separated; during them the uncertainties of the ages cause an apparent mixing of polarities even if they are in reality periods of consistent reversal. The extent of the mixing allows the uncertainty of the potassium–argon dates to be estimated; the result, $3\frac{1}{2}\%$ or 100 ky, whichever is the greater, is consistent with estimates based on the errors of measurement and on the agreement of several specimens from the same lava flow (Cox & Dalrymple 1967*a*). It is, of course, possible that there are other as yet undiscovered events, in fact there is a flow in Iceland that has a normal polarity and an age of 1·6 My (McDougall & Wensing 1966). This flow may represent an event which has been named the Gilsa event, however, Icelandic lavas have an undesirably low content of potassium and this flow contains some glass; it is possible that the age is in error, though another example of a normally magnetized flow of the same age has been found recently on Nunivak Island by Cox & Dalrymple (1967*b*). There is also a reversely magnetized Haiwaiian lava with an age of 2·8 My which may represent another event, the Katna event (McDougall & Chamlaun 1966).

The data from lavas leave something to be desired. The outflow of lava from a volcano is an intermittent process and a pile of flows does not give a continuous sequence; the interval between two successive flows may be 6 months or a 100 ky and it is not easy to estimate how large it is. Moreover, it is not possible to say which of two flows is the older unless one lies on top of the other or unless the age difference is sufficient to be detectable by potassium–argon dating. Fortunately the examination of sediments from the deep sea gives an independent method of studying reversals which has confirmed the results from the lavas.

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4. Reversals in deep-sea sediments

Sediments accumulate in the deep ocean at rates of 1 to 10 mm in 1000 years (Goldberg & Koide 1962; Dymond 1966). The most recent reversal, which occurred about 700 ky ago, will therefore be found at a depth of 0·7 to 7 m and the transition between the Gauss and Gilbert epochs will be at a depth between 3 and 35 m. If a core of ocean sediment is to contain a record of the Pleistocene and Pliocene reversals found in lavas it should be as long as possible and should be taken in sediment that is deposited slowly and contains a fair proportion of magnetic material. These criteria suggest the use of cores of red clay. Since the inclination of the magnetization is easier to measure than the declination and is less likely to be disturbed in coring, it is desirable to avoid cores taken near the equator.

Early work showed no reversals, probably because the cores were too short (McNish & Johnson 1938; Johnson, Murphy & Torreson 1948; Keen 1960, 1963). The first observation of a reversal in a core was by Harrison & Funnell (1964) who observed five reversals in cores of clayey radiolarian ooze from the equatorial Pacific. More detailed observations on longer cores have been made by Dickson & Foster (1966); Harrison (1966); Harrison & Somayajulu (1966); Ninkovich, Opdyke, Heezen & Foster (1966); Opdyke, Glass, Hays

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& Foster (1966); Hays & Opdyke (1967); Watkins & Goodell (1967*a*, *b*, *c*) and Berggren, Phillips, Bertels & Wall (1967); Goodell & Watkins (1968). Results from a core 13 m in length taken in the North Pacific about 1000 km south of the Aleutians are shown in figure 2; the figure shows the magnetic dip measured on samples taken at intervals of 10 to 20 cm in depth (2 cm in the neighbouhood of reversals). For the upper 5 m of the core the dip has the normal, downward, direction and fluctuates between about 40 and 60° with a mean of about 52°, which is not far from the present dip of 57°. At a depth of 525 cm the dip changes sign and remains negative till 678 cm where it again reverses to the normal direction where it remains for the next 34 cm. It then reverses again and remains so till near the bottom of the core where a further transition to the normal direction occurs. All these changes are shown by other cores from the same area and also by cores from other parts of the world; they clearly represent a general phenomenon and not a peculiarity of the individual core. The spike at about 800 cm is peculiar to this core and presumably represents a disturbance produced in coring or, conceivably, a disturbance of the sediment while on the sea floor.

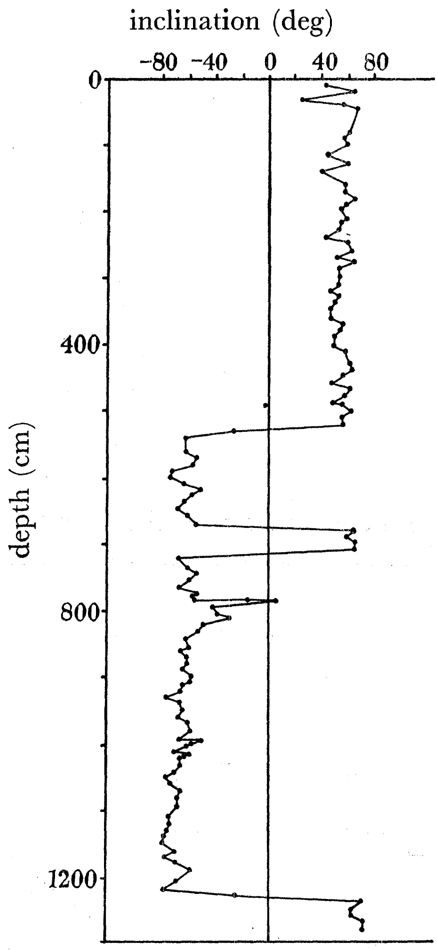

FIGURE 2. Dip of the magnetization of a core from the North Pacific (from Ninkovich *et al.* 1966).

It is natural to correlate the upper transition with the Brunhes–Matuyama transition found from the lavas at 700 ky before the present, the brief return to normal with the

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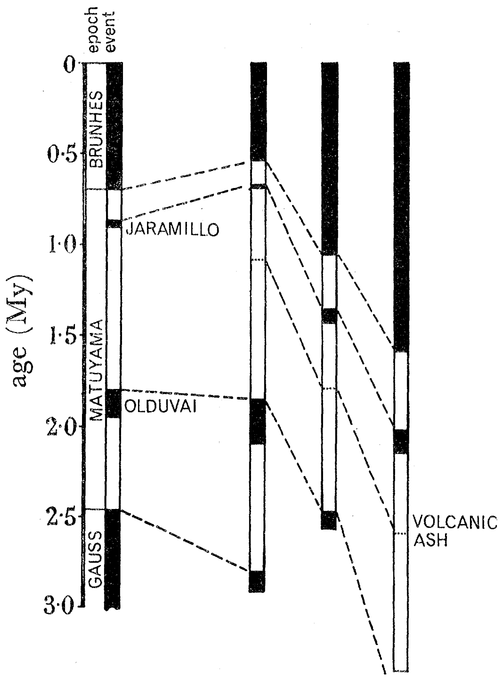

Figure 3. Comparison of three cores from the North Pacific with the time scale of reversals deduced from lavas (from Ninkovich *et al.* 1966). Black sections are normally magnetized, white ones are reversed.

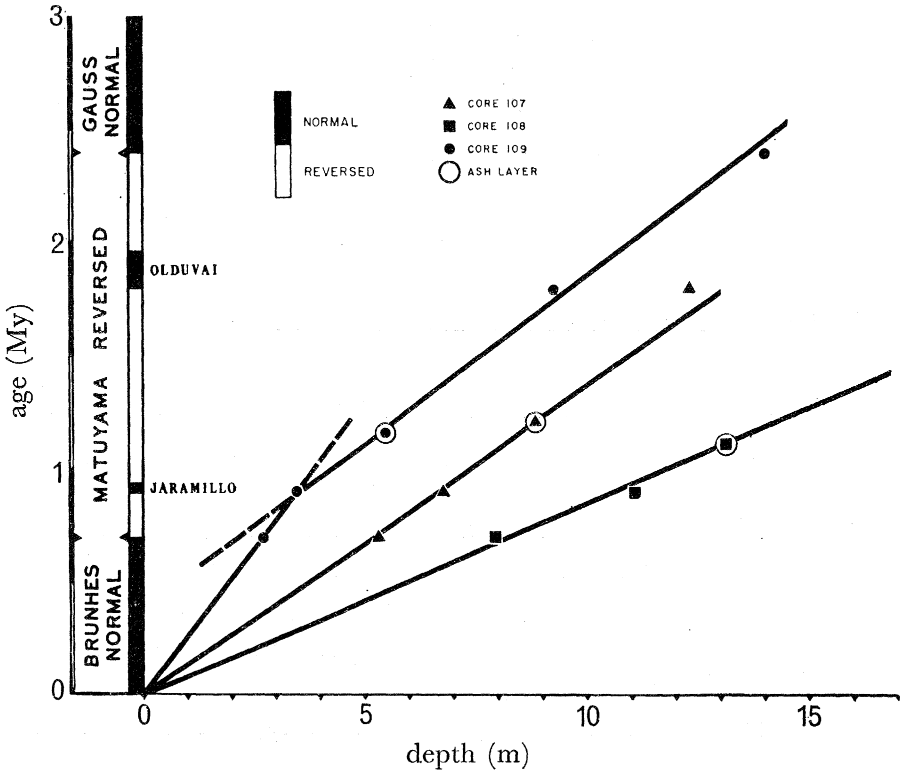

Figure 4. Rate of sedimentation from the cores shown in figure 3 (from Ninkovich *et al.* 1966).

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Jaramillo event and the final short piece of normally magnetized sediment at the bottom with the Olduvai event at 1·8 My. These correlations for this and two other cores from the same region are shown in figure 3. The progress of sedimentation in three of the cores is shown in figure 4; two of the cores give constant rates of 0·75 and 1·13 cm/ky, the third gives 0·36 in the upper part and 0·80 in the lower. The correctness of the correlations is confirmed by the occurrence of a well-marked ash band at depths corresponding to about 1·2 My in the three cores. Measurements going back about 5 My, that is to a time before the start of the Gilbert epoch, have been obtained by Hays & Opdyke (1967), they find three well marked events of normal magnetization in the Gilbert epoch. The results constitute a striking confirmation of the sequence of reversals deduced from the magnetization of lavas. No two substances could be more different or have more different histories than the lavas of California and the pelagic sediments of the Pacific. The lavas were poured out, hot and molten, by volcanos and magnetized by cooling in the Earth's field; the ocean sediments accumulated grain by grain by slow sedimentation and by chemical deposition in the cold depths of the ocean. If these two materials tell the same story then it must be the story of an external influence working on both and not a story of recurrent synchronous change in the two materials. The evidence compels belief in reversals of the Earth's field as the cause of these reversals of magnetization.

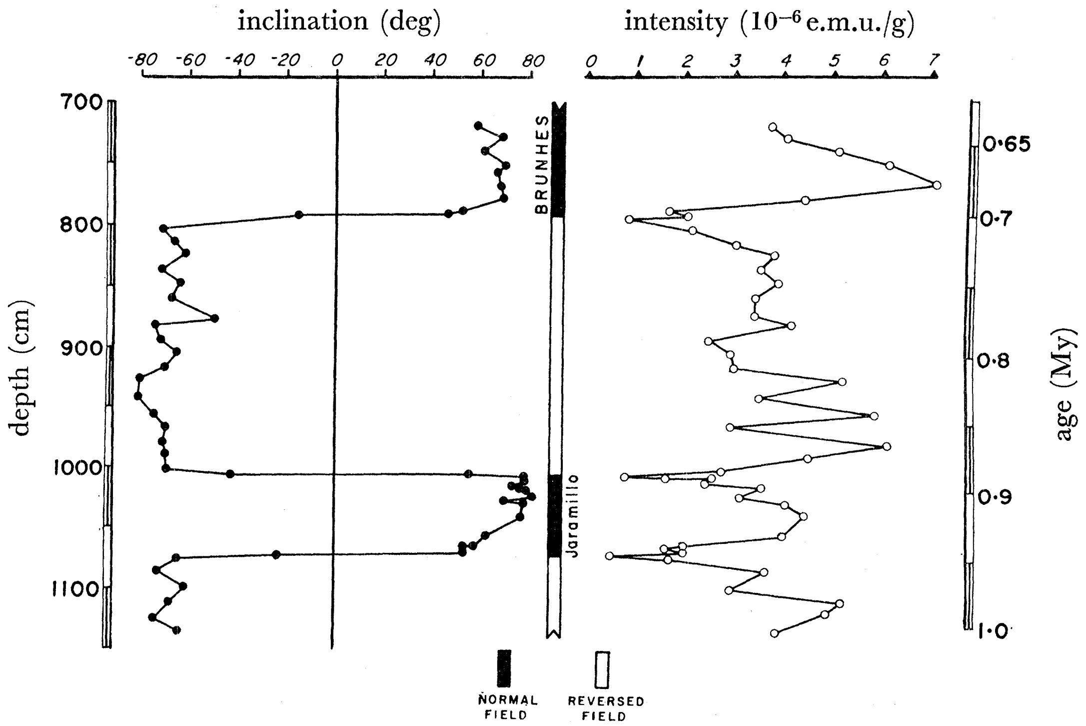

FIGURE 5. Dip and intensity of magnetization of a portion of a core from the North Pacific (from Ninkovich *et al.* 1966).

The accuracy, continuity and detail available in data such as that in figure 3 can be used in many ways. Clearly the reversals are nearer to sudden transitions than to simple harmonic oscillations. This is shown still more clearly in figure 5, which shows the dip and intensity of magnetization for a portion of a core taken at a point about 250 km to the north of that

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shown in figure 3; for this core samples were taken at 1 cm intervals in the neighbourhood of the reversals. It seems that a large part of the change in dip takes place in a time interval of 1 ky. The change in intensity of magnetization of the sediment is shown on the right of figure 5; in a uniform sediment this provides a measure of the magnetizing field. The magnetization is very variable but shows its lowest values at the times of reversals; this had previously been demonstrated by van Zijl, Graham & Hales (1962*a*, *b*) for the Stormberg lavas of the Transvaal. At these minima the magnetization is 10 to 20 % of its normal value. The intensity of the field begins to fall before there is any large change in dip and continues to increase after the dip has completed its transition; the total time taken for the magnetization to decrease and recover is about 40 ky and is several times larger than the time required for the reversal of the dip.

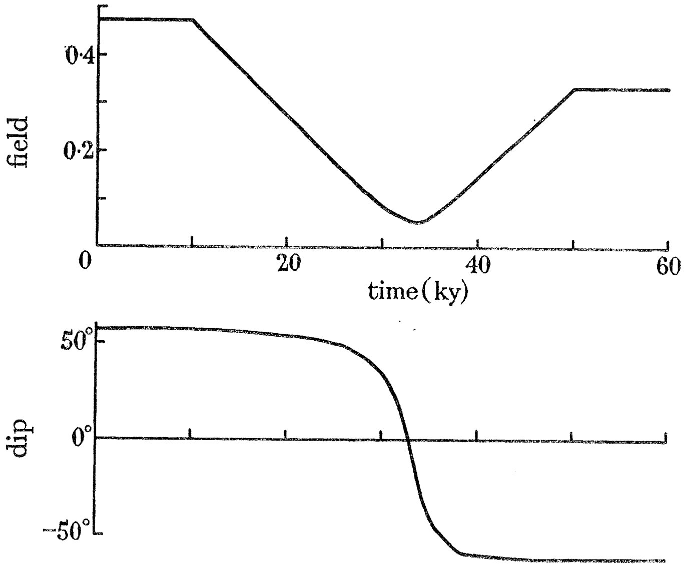

FIGURE 6. Change of dip and field intensity if a field of 0·4 G reverses in 40 ky in the presence of a constant field whose north, east and vertical components are equal and are all 0·05 G.

There are two extreme ways in which a vector field can reverse: it can swing round without change in magnitude or it can decrease without change in direction, pass through zero and then grow in a direction opposite to its intial direction. The observed behaviour is nearer the second of these, which would give a discontinuous change in dip as the field passed through zero however slowly the field decayed. The observed behaviour is compatible with a reversal of the dipole field accompanied by the usual fluctuating non-dipole field. Figure 6 shows the course of events if a field of 0·4 G decays linearly and grows again in 40 ky in the presence of a small constant field. More realistic calculations with a fluctuating non-dipole field are easily made.

The reversal of dip in about 1000 years is surprising from another point of view. Any mixing of sediment by marine animals, such as mud-eating worms, will make the transition less sharp than it would be in undisturbed sediment. It is usually supposed that the mottled appearance of the material in most cores is due to this mixing process and indicates that it extends over about 3 cm (see, for example, the reproduction by Ninkovich *et al.* (1966) of photographs of parts of the cores from which the data of figures 2 and 5 were taken). It is

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also surprising that the dip is so close to that measured today; it would be expected that compaction would reduce it. It is conceivable that the magnetization occurs some time after burial either by the magnetization of crystals forming slowly in the sediment or by the grains remaining mobile till they are locked by compaction.

Comparison of the depths of magnetic transitions with the dates from lavas on land allows rates of sedimentation to be determined. They are of the same order (1 to 10 mm/ky) as those found by other methods and vary from one core to another; they do not, however, show the variation that might be expected from the large fluctuations in the climate during the Pleistocene. It is likely that the climate varies on a shorter time scale than the magnetic reversals and that the fluctuations in rate of sedimentation are averaged out. The durations of the 'events' are too short to be found with any accuracy from the dating of lavas, better estimates can be obtained from the cores, assuming a constant rate of sedimentation. The Jaramillo event seems to have lasted about 50 ky and the Olduvai event about 140 ky.

In the detail of the results there are a number of perplexing discrepancies which have been discussed by Evans (1969); Dickson & Foster (1966) get a poor correlation between measurements of declination and dip, Ninkovich *et al.* (1966) find the Olduvai event to be double, whereas Dickson & Foster do not, Opdyke *et al.* (1966) have a core that shows neither the Jaramillo nor the Olduvai event, Watkins & Goodell (1967*b*) have found evidence for the Gilsa event in their cores which others failed to observe. These discrepancies are presumably due to defects in coring technique and, perhaps some of them, to irregularities in sedimentation. In principle, coring is simple: a tube is driven into the sea floor and brings up an undisturbed sample of sediment. In practice, it is a skilled and somewhat chancey operation. Cores taken with a free fall corer are usually too short to reach the first reversal and almost always give a core that is shorter than the depth of penetration, the shortening is not uniform and may be achieved by the squeezing out of soft bands (Emery & Dietz 1941; Ross & Riedel 1967). Piston corers (Kullenberg 1947) can give a much greater penetration but frequently 'suck in' sediment which is grossly disturbed and may be out of place if the suck occurs as the corer is being withdrawn. There is some risk of the polarity-time scale being reduced to chaos by attempts to correlate spurious events produced by uncertainties in potassium argon dating of lavas with apparent reversals of magnetization in sediments due to disturbances in coring. There are also possibilities of disturbances of the sediment on the sea floor due to the removal or addition of material by slumping or turbidity currents. In view of the importance of getting reliable results a substantial effort to improve the techniques of taking cores and dating lavas would be justified. Even if no improvement were made in the technique of coring, a recorder that gave the motion of the coring tube and of the piston relative to the sediment outside the tube as a function of time would make it easier to select cores meeting the very exacting requirements for the study of the history of reversals. A reliable method of dating cores independently of correlation with the lavas would remove many doubts. It seems unlikely that the ionium method can give reliable results for material more than 500 ky old (Goldberg & Koide 1962), perhaps the best prospect is the dating of bands of volcanic ash by the potassium–argon method (Dymond 1966).

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5. The magnetic pattern on the ocean floor

A large part of the floor of all the oceans is covered by a magnetic pattern in the form of parallel stripes. One of the most significant discoveries of recent years is that this pattern repeats again the same story of reversals in the Earth's magnetic field as is told by the lavas on land and the sediments beneath the ocean floor. This zebra-like pattern was first seen in the magnetic surveys off the Pacific coast of North America conducted by the Scripps Institution and the U.S. Coast and Geodetic Survey (Mason 1958; Mason & Raff 1961; Raff & Mason 1961; Vacquier, Raff & Warren 1961; Raff 1962, 1966; Peter & Steward 1965; Talwani, Le Pichon & Heirtzler 1965; Peter 1966; Elvers, Mathewson, Kohler & Moses 1967). The pattern shows a marked north-south lineation extending 3700 km from Mexico to the Aleutians. It is broken into blocks by 'fracture zones', but, in spite of this, individual stripes can be traced over the whole distance and probably extend further into unsurveyed areas. The fracture zones are clearly faults which appear as scarps on the sea floor. At these scarps the magnetic pattern is offset, sometimes by as much as 1200 km. Unlike the fracture zones, the magnetic pattern itself is not related to the topography of the ocean floor (figure 7) or of a surface buried beneath the sediments. For reasons that have only recently become clear, some critical features of the pattern do not appear off the Californian coast. It was the measurements of Heirtzler, Le Pichon & Baron (1966) over the Rykjanes Ridge to the south of Iceland which first showed the phenomenon in its clearest and simplest form. Here, as is shown in figures 8 and 9, the magnetic stripes run parallel to the axis of the mid-Atlantic Ridge and are almost exactly symmetrical about it. Similar patterns have been found in all the oceans (Heirtzler & Le Pichon 1965; Matthews, Vine & Cann 1965; Bowin & Vogt 1966; Cann & Vine 1966; Pitman & Heirtzler 1966; Demenitskaya 1967; Elvers *et al.* 1967; Grimm & Erickson 1967; Heirtzler & Hayes 1967; Schlich & Patriot 1967; Rassokho *et al.* 1967; Uyeda *et al.* 1967). There is some difficulty in adequately representing these patterns. Individual profiles, such as those of figure 8 contain noise from the magnetic effects of the topography and magnetic variations during the survey. On the other hand, maps, such as that of figure 9, showing merely areas of excess and defect of field often break up the stripes into blobs because a peak just fails to reach the zero line; this fault is accentuated by a slight general depression of the field over the crest of the ridge, perhaps due to the Curie point being nearer the surface there than elsewhere (Heirtzler & Le Pichon 1965). A detailed contoured map requires more information and better navigation than is usually available.

The straightness, symmetry, extent and ubiquity of these patterns is without parallel in geology and their discovery was completely unexpected. Nothing like them is known on the continents and they must be an expression of some world-wide oceanic process. The nature of this process was first suggested by Vine & Matthews (1963) largely on the basis of measurements made from H.M.S. *Owen* in 1962 during the International Indian Ocean Expedition. An area about 50 × 40 miles on the crest of the Carlsberg Ridge in the north-west Indian Ocean was surveyed in detail (Matthews *et al.* 1965); it was found that the magnetic effects of individual topographic features could be picked out and that some were normally magnetized and some reversely (Cann & Vine 1966). With this as a clue, Vine & Matthews (1963) suggested that the pattern of linear anomalies is due to strips of the sea

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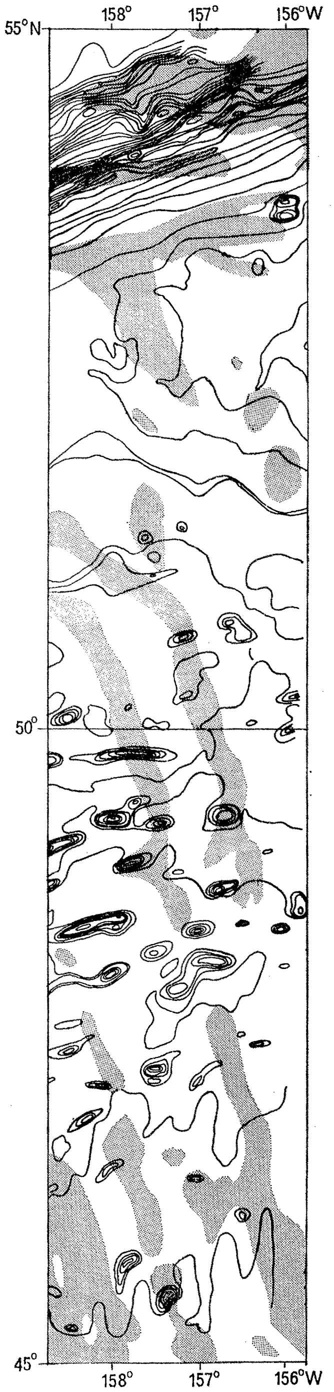

FIGURE 7

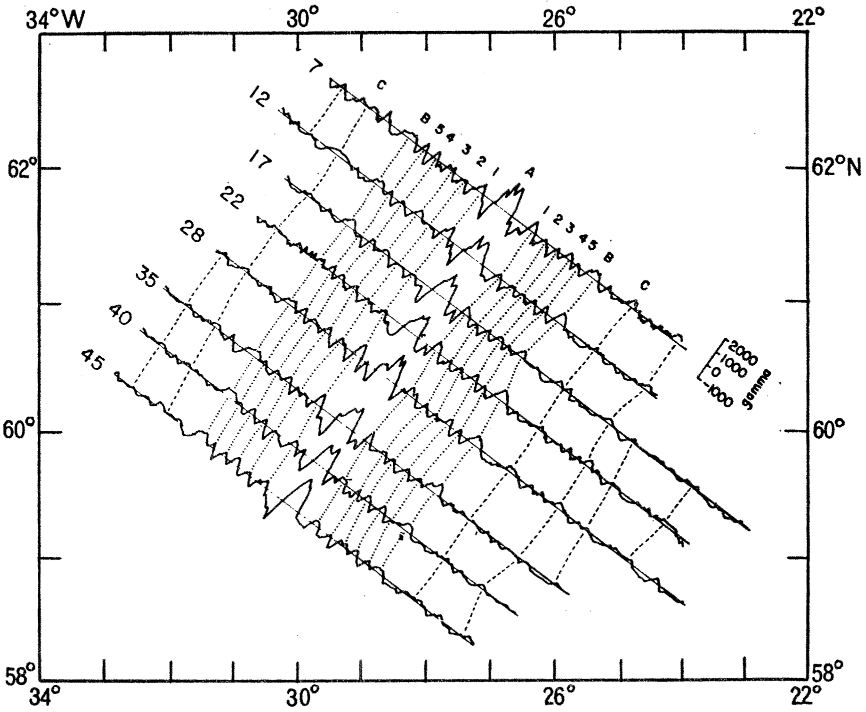

FIGURE 8

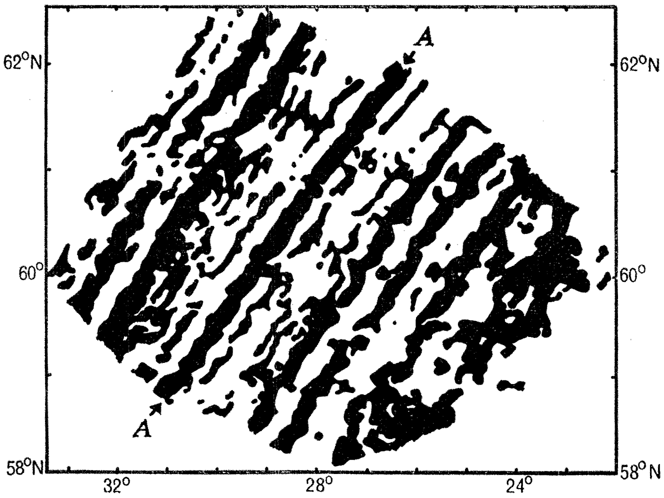

FIGURE 9

FIGURE 7. A portion of the magnetic pattern off the west coast of North America showing the lack of relation to topography. The contours represent the topography and the shading the regions of high magnetic field (from Peter & Stewart 1965).

FIGURE 8. Eight of the 58 profiles of total magnetic force across the Reykjanes Ridge to the south of Iceland projected on lines at right angles to the ridge. Note the continuity of the anomalies along lines parallel to the axis of the ridge (marked *A*) and the symmetry about this axis (from Heirtzler *et al.* 1966).

FIGURE 9. The magnetic pattern over the Reykjanes Ridge. Areas of positive anomaly in the total force are black. *A*–*A* is the axis of the ridge (from Heirtzler *et al.* 1966).

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floor being magnetized in opposite directions. They explained the existence of such strips by combining the reversals of the magnetic field with the ideas of sea floor spreading.

Sea floor spreading was first suggested by Dietz (1961) and Hess (1962, 1965), the claim that the idea can be found in much earlier papers (e.g. Holmes 1931) seems to me not to be well founded. Dietz and Hess suggested that mantle material rises under the mid-ocean ridges, spreads out horizontally near the surface and produces a drag on the surface material which causes cracks along the axis of the ridge as is shown in figure 10. The crack is filled with igneous rocks from below, which are again cracked by the same process. Thus at any time the youngest material is on the axis of the ridge and older material is carried away on both sides. Such a picture unifies many aspects of marine geology. The mid-ocean ridges do very commonly have a central valley floored by young igneous rocks and young sediments and the sediments on either side do increase in age as one recedes from the ridge (Burckle, Ewing, Saito & Leyden 1967; Funnell 1968). The flow of heat from the interior of the Earth is exceptionally high over the axis of the ridge. The majority of mid-ocean earthquakes are rather accurately located in the central valleys of the mid-ocean ridges and give 'first motions' which show that they are associated with the opening of a crack (Sykes 1967); the remainder of the earthquakes occur on the fracture zones which traverse and offset the ridge axis, the first motions show them to be transform faults (Sykes 1967) as predicted by Wilson (1965*a–c*). In recent years the idea has been elaborated in connexion with continental drift; spreading of the ocean floor does not imply continental drift, but is compatible with it. A convection current rising under a ridge might dive down again at the edge of a continent, without moving it, but producing stresses, an ocean deep and deep earthquakes; that is, producing a 'Pacific' type of coast line in the sense of Suess (1888). On the other hand the horizontal limb of the convection current might continue under the continent and only sink when it encountered an oppositely moving limb under the ocean on the far side of the continent. The continent would then be transported, as on a conveyor belt, with no large stresses, except perhaps at its leading edge.

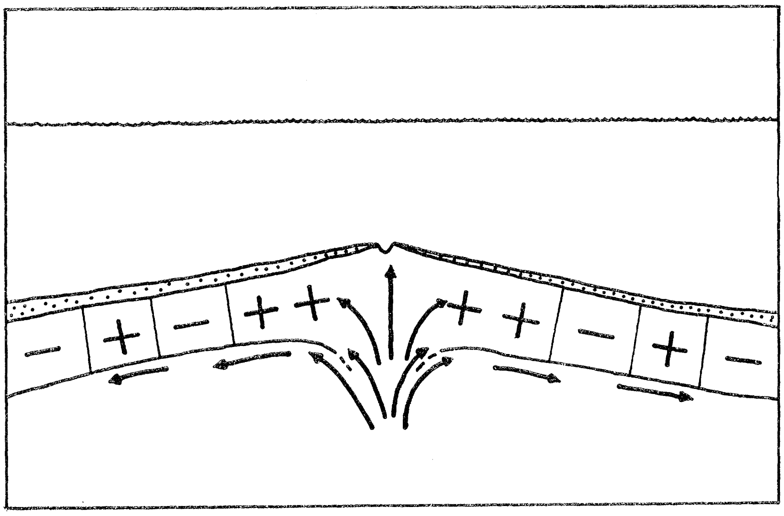

FIGURE 10. Cracking at the axis of the ridge and the production of oppositely magnetized stripes.

There are difficulties in these views. To discuss them in detail would take us too far from our main theme. Perhaps the most serious is the dredging of Miocene globigerina ooze

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incorporated in a piece of volcanic glass from a fracture zone near the axis of the ridge in the South Atlantic (Ewing, Le Pichon & Ewing 1966; Saito, Ewing & Burckle 1966). If the fracture zone is a transform fault as in figure 11, rocks of all Tertiary ages will have moved past it and it is not impossible that pockets of older rocks will survive along the fault. Alternatively, it is a little suspicious that a specimen of an identical, very rare rock should have been dredged on the same expedition 130 km from the axis of the ridge; it is perhaps conceivable that both bits came from the latter haul. A basalt with an age of 27 My was dredged from Cobb seamount. According to Budinger & Enbysk (1967) this seamount is associated with the axis of the Juan da Fuca Ridge, however their diagram shows it to be 100 km to the west of the axis. In any case, the rock may well be an erratic since, according to Heirtzler *et al.* (1968), drilled samples from the seamount give an age of 2 My. Such explanations may appear a little forced, but the few discrepancies must be viewed against the background of hundreds of cores and dredge hauls that give the expected results; odd things must be expected to occur occasionally.

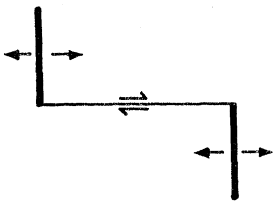

FIGURE 11. A transform fault joining two sections of a ridge.

Another unexpected result is the lack of disturbance of the sediment in the ocean trenches (Ewing & Ewing 1967*a*; Huene *et al.* 1967; Scholl *et al.* 1967), if the material spreading from the East Pacific Rise is really diving beneath South America and if South America is advancing into the Pacific it is difficult to see how the sediments can remain undistorted for any long period. It would be interesting to know the age of the undistorted material.

The essential suggestion of Matthews and Vine was that the new material on the axis of the ridge would always be magnetized in the direction of the magnetic field at the time of injection and that the history of the reversals would be spelt out by the horizontal transport of the magnetized rock, in a way similar to the recording of a message by a tape recorder (figure 10). This hypothesis has been brilliantly verified by Vine & Wilson (1965), Vine (1966) and by their followers (Pitman & Heirtzler 1966; Heirtzler 1967; Krause 1967; Phillips 1967; Dickson *et al.* 1968; Heirtzler *et al.* 1968; Le Pichon & Heirtzler 1968; Pitman *et al.* 1968). The last four papers collect and summarize all the material; I am grateful to Dr Heirtzler for letting me see them before publication.

If the hypothesis is correct it should be possible to predict the results of magnetic surveys from the sequence of reversals. Four examples from widely separated parts of the ridge are given in figure 12, in which the second line shows the observed variation of the magnetic field across the ridge. The top line is identical to the second one turned end to end, the close similarity of the two shows the high degree of symmetry about the axis of the ridge. At the bottom of the figure is the pattern of reversals deduced from the magnetization of lavas on land, above this is the magnetic profile calculated on the assumption that there are blocks of normally and reversely magnetized lava under the ocean floor corresponding

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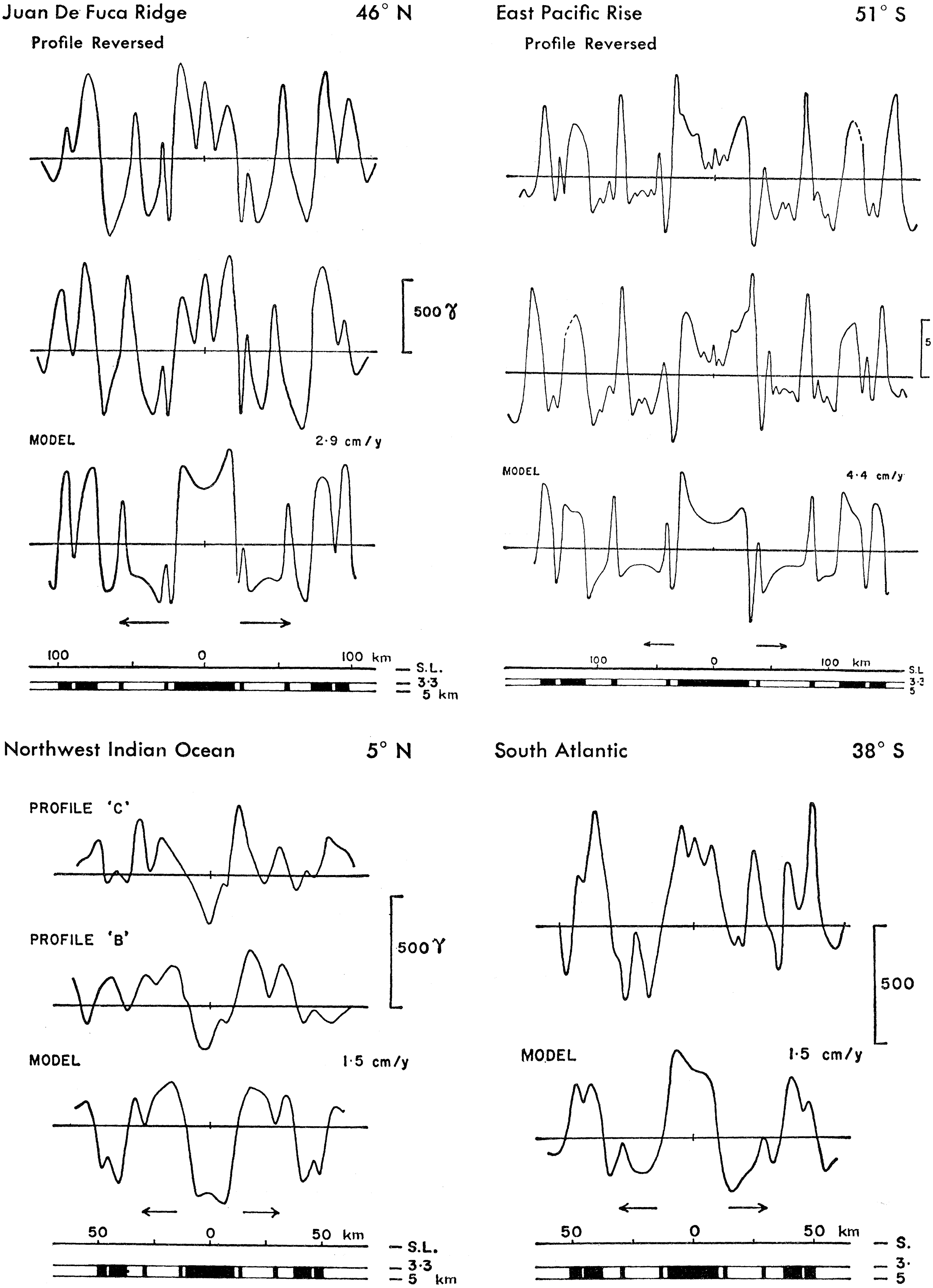

Figure 12. Magnetic profiles (total force) along tracks crossing the mid-ocean ridges. The top line in each section is the observed profile reversed (note the symmetry). The third line is the profile calculated from the pattern of reversals deduced from the study of lavas on land, which is shown at the bottom of each section on an appropriate scale (from Vine 1966).

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to the pattern of field reversals. The agreement of these calculated profiles with the observed ones is very striking and about as good as that between the direct and reversed profiles. Exact symmetry would only be expected where the ridge runs in a north–south direction, but in fact the departures from symmetry are quite small in both the calculated and the observed profiles; they are most easily seen in the peak over the central valley, the form and amplitude of which have been investigated in detail (Heirtzler & Le Pichon 1965) and are fully accounted for by a block under the valley magnetized in the direction of the present field. As would be expected a north–south ridge gives no coherent pattern in the neighbourhood of the equator (Vacquier 1965).

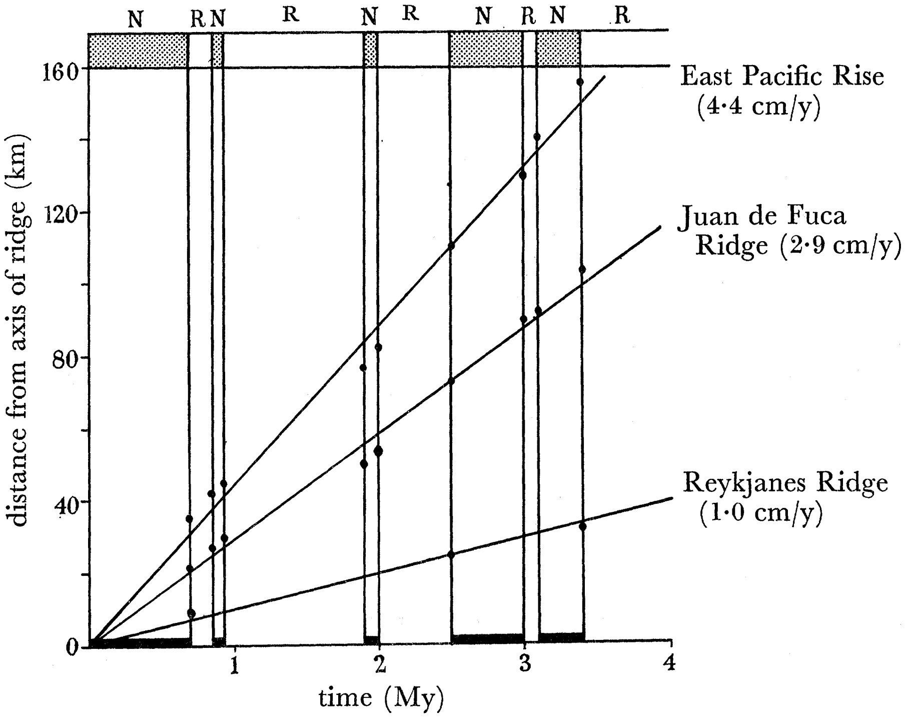

Figure 13. Plots of the distance of magnetic stripes from the ridge axis against times for the corresponding field reversals determined from the ages of lavas on land (from Vine 1966).

To predict the results of magnetic surveys from measurements on rocks thousands of miles away is a claim so exorbitant in a subject where things are rarely clear-cut or predictable, that it is necessary to be very sure that we are not deceiving ourselves. The agreement of the calculated and observed curves is so good that it seems impossible to ascribe it to chance. One could wish in this and other geophysical contexts that there were objective criteria for describing the resemblance of curves; the matter is one of some difficulty, the obvious criteria, using cross-correlation, are not very useful because they are dominated by the central peak and give little weight to the agreement of small peaks. Also cross-correlation is grossly disturbed by a little irregular stretching of the curves such as might be produced by slight variations in the velocity of spreading of the ocean floor. Similarity is not a simple idea, and is only partly metrical; it is concerned with the number and sequence of maxima, minima and zero crossings as well as with their positions and amplitudes. It may be quite difficult to formalize intuitive impressions about it, perhaps ideas from the detection of bomb tests by seismic arrays and from numerical taxonomy may be fruitful.

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It is important also to consider how many adjustable parameters are involved in the calculations; anything can be fitted convincingly to almost anything if enough arbitrary constants are available. In comparisons such as those of figure 12 there are two essential quantities to be determined in making a fit, the horizontal scale, that is the velocity of spreading, and the intensity scale, that is the intensity of magnetization of the rock. It might be imagined that the velocity of spreading would vary from time to time and that it would be necessary to assume a more or less complicated and arbitrary velocity–time curve. In fact, this is not so over the period of $3\frac{1}{2}$ My shown in the comparisons of figure 12. In that figure a constant velocity has been assumed for each profile; if the distances from the axis of the ridge are plotted against the times of reversal the points lie very well on straight lines (figure 13).

In the comparisons of figure 12 the intensities of magnetization of all blocks, except the central one on each profile, have been taken to be 0·005 e.m.u. The central block has been assumed to have twice the intensity of the other blocks, this assumption is necessary since the magnetic anomaly over the central valley is nearly always much greater than the peaks in the rest of the pattern. An increase for the central valley is plausible since there will not, in reality, be a succession of completely separate blocks but a series of more or less overlapping lava flows fed by many feeder dykes; the central valley of the ridge may be floored entirely by recent lavas but on each side there will be overlapping with older lavas. Matthews & Bath (1967) and Vine & Morgan (1967) have made calculations of the effect of a statistical distribution of intrusions and conclude that the feeder dykes may be spread over a few kilometres. Mudie & Harrison (1967) have made measurements of the magnetic field near the ocean floor using a towed, deep-diving magnetometer; they find a fine structure in the pattern which probably represents the effects of individual dykes and flows. It is perhaps fortunate that this fine structure is not apparent in observations made near the surface of the sea; had it been, the elegant regularities of the large-scale pattern would have been much less apparent.

The depths of the upper and lower surfaces of the magnetized blocks are also, in principle, variable, but in practice these parameters are of little significance. The thickness of the sediment on the deep ocean floor is usually only a few hundred metres and is almost always much less than the depth of water; the upper surface of the blocks can therefore be taken as at the sea floor or a few hundred metres beneath it. The position of the lower surface of the blocks has little effect on the form of the curves. In figure 12 the upper and lower surface of the magnetized blocks have been assumed to be 3·3 and 5 km below the surface of the sea. It is possible that allowance for the actual form of the upper surface would improve the agreement, for example Vine & Wilson (1965), by allowing for the topography of the Juan da Fuca Ridge, get a triple central peak, as in the observed profile of figure 12. It might be argued that the lower surface of the blocks should be deeper, the 5 km depth was chosen under the influence of Hess's (1962, 1965) opinion that on the ocean floor a few kilometres of basalt overlie almost non-magnetic serpentine, if the seismologists' 'layer 3' is basalt a greater depth should be taken.

Other adjustable parameters are involved in removing the 'trend' from magnetic surveys to get anomalies; the procedures commonly used are not very satisfactory but the arbitrariness can be completely avoided by using a world-wide reference field to remove

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trend or by numerical smoothing over distances large compared to the features being studied (Bullard 1967*a*). In summary the comparisons in figure 12 involve one adjustable constant per profile which fixes the horizontal scale and two more for the whole set, one of which fixes the vertical scale and the other the factor of two in the magnetization of the central blocks. Such an exiguous number of adjustable quantities, which are just those essential to the theory, can scarcely have produced the numerous coincidences of peaks seen in the figures. We therefore conclude that the hypothesis of Vine & Matthews, that the magnetic pattern found at sea is due to field reversals and spreading of the ocean floor, is verified.

The hypothesis was, very naturally, at first received with some scepticism (see, for example, Talwani, Le Pichon & Heirtzler 1965). Most of the original doubters have now been converted, but there have been some recent, though rather half-hearted, attempts at alternative theories by Watkins (1968) and Ozima *et al.* (1968). They suggest that the magnetic pattern may be due to the intrusion of dykes along a system of fractures in a 'crustal plate'. I find it difficult to imagine a system of tensile fractures so regular that a series of thirty or more of them will run parallel at a separation of a few tens of kilometres for a distance of thousands of kilometres without running into each other. The main difficulty is not, however, these mechanical improbabilities, but the impossibility of explaining the bilateral symmetry of the patterns, their similarity all over the world and the detailed agreement with Vine's models. A real reason for doubt is the difficulty of explaining by ocean floor spreading the sharp bend in the anomalies in the northeast Pacific, where they swing from roughly north-south to east-west (figure 14) with no magnetic or topographic signs of disruption or crumpling. On the Matthews–Vine hypothesis these anomalies are probably over 60 My old and long antedate the formation of the Aleutian arc and the arrival of America in its present position. It is far from clear what has happened to the associated ridge, which now extends only to the latitude of the north end of Vancouver Island, or where it was when the pattern was formed. The detailed publication of the results, particularly of the individual magnetic and topographic profiles, is clearly of high importance. The geometry of the bend does pose a serious problem, but it seems rash to throw over the very clear conclusions from so large a body of data on this ground alone.

If the Vine–Matthews hypothesis is accepted the whole history of the ocean floors is open to investigation. The rates of spreading to each side of the ridge during the last $3\frac{1}{2}$ My for the sections of ridge so far investigated are given in table 3. The rate of spreading from the East Pacific Rise averages 3·8 cm/y and is two to three times greater than that from the ridges in the Atlantic and Indian Oceans. There are a number of other ways in which the East Pacific Rise differs from the mid-Atlantic and Carlsberg Ridges (Phillips 1967), but the significance of these is not clear. From a comparison of the magnetic pattern off the coast of California with that farther north it seems that only the west part of the pattern is present and that this part of the East Pacific Rise has been overrun by the westward drift of North America and now lies under Utah and Arizona (Vine 1966). A similar conclusion had been reached earlier by Menard (1964) from a study of the topography, which is characteristic of the western flank of a ridge.

Very recently Heirtzler *et al.* (1968) have attempted to correlate all known magnetic profiles across the ridges. Here the emphasis has shifted, the primary object is no longer to confirm or refute the Vine–Matthews hypothesis; the hypothesis and the spreading of the

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ocean floor are assumed to be of general application. The object is to see further into the past and to get an idea of the rates of spreading and of the ages of the ocean floor for the last 50 to 80 My. Often the correlations are very clear even in the oldest part of the pattern, for example, figure 15 shows that the curves from the North Pacific are similar in almost every detail to those taken south-east of New Zealand, these parts of the pattern are believed to have been formed 60 to 80 My ago. In many places the correlations are not so clear, here what seems the most plausible choice has been made. If these correlations are accepted it seems that the whole of the east and south Pacific, the southern and western parts of the Indian Ocean and a central strip of the Atlantic are covered by a correlatable pattern.

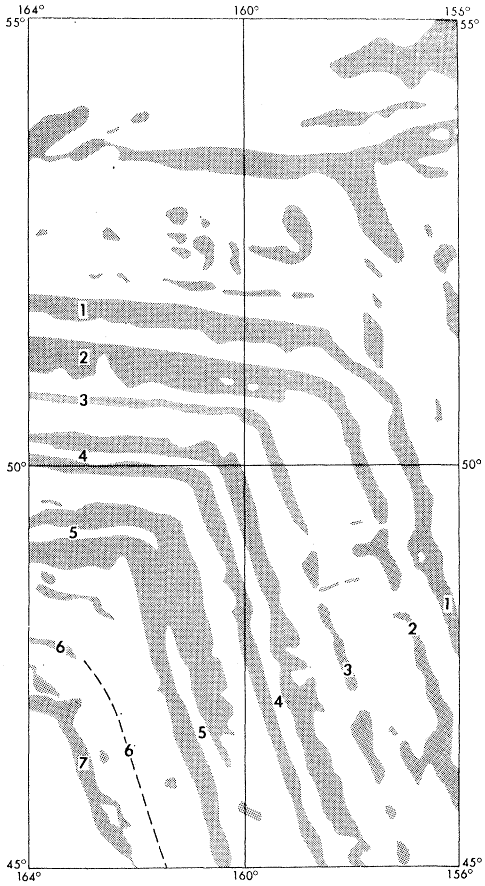

FIGURE 14. Bend in the pattern of anomalies to the south of the Aleutians (from Elvers *et al.* 1967).

The eastern sector of the Arctic Ocean has a remarkable pattern (Demenitskaya 1967; Rassokho *et al.* 1967) which no one has attempted to correlate with that in the other oceans. There is also a pattern in the north-west Pacific (Uyeda *et al.* 1967). The north-eastern Indian Ocean appears to have no comparable pattern; it is not clear whether there is a pattern in the Indian Ocean south of Africa. Unpublished profiles from operation NAVADO (a joint project of the British and Dutch navies) show an extensive pattern in the North Atlantic but, on a cursory examination, some of them show no clear symmetry. Ewing & Ewing (1967 *b*) have suggested, from a study of the sediments, that spreading in the Atlantic may have been intermittent. Clearly the exact delineation and interpretation of the pattern over all the oceans is an enormous undertaking that will take decades to complete, most of

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the present information is in the form of isolated profiles separated by hundreds of kilometres, the surveys of the north-west Pacific and of the Rykjanes Ridge show how much more instructive are surveys in which the lines are 10 km or less apart.

Table 3. Rate of spreading from the ridge axis during the last 3·5 My

ocean	lat.	long.	rate (cm/y)	ref.	notes
Atlantic	60° N	28° W	1·0	1	Reykjanes Ridge
	27° N	44° W	1·25	2, 5	—
	22° N	45° W	1·40	2, 5	—
	25° S	13° W	2·25	5	—
	28° S	13° W	1·95	5	—
	30° S	14° W	2·0	5	—
	38° S	17° W	1·5	1	—
	38° S	17° W	2·0	5	—
	41° S	18° W	1·65	5	—
	47° S	14° W	1·60	5	—
	50° S	8° W	1·53	5	—
Indian	19° N	40° E	1·0	1, 5	Red Sea
	16° N	41° E	1·0	1	Red Sea
	13° N	50° E	1·0	5	Gulf of Aden
	7° N	60° E	1·5	5	Carlsberg Ridge
	5° N	62° E	1·5	1, 5	Carlsberg Ridge
	22° S	69° E	2·2	5	Chagos-St Paul Ridge
	30° S	76° E	2·4	5	Chagos-St Paul Ridge
Pacific	46° N	130° W	2·9	1	Juan de Fuca Ridge
	42° N	127° W	1·0 to 3	4	Gorda Ridge
	17° S	113° W	6·0	5	E. Pacific Rise
	40° S	112° W	5·1	5	—
	45° S	112° W	5·1	5	—
	48° S	113° W	4·7	5	—
	51° S	117° W	4·9	5	—
	51° S	117° W	4·4	1, 3	—
	58° S	149° W	3·8	5	—
	60° S	150° W	4·0	5	—
	63° S	167° W	2·3	5	—
	65° S	170° W	2·0	5	—
	65° S	174° W	2·8	5	—

1, Vine (1966); 2, Phillips (1967); 3, Pitman & Heirtzler (1966); 4, Menard (1967); 5, Heirtzler *et al.* (1968)

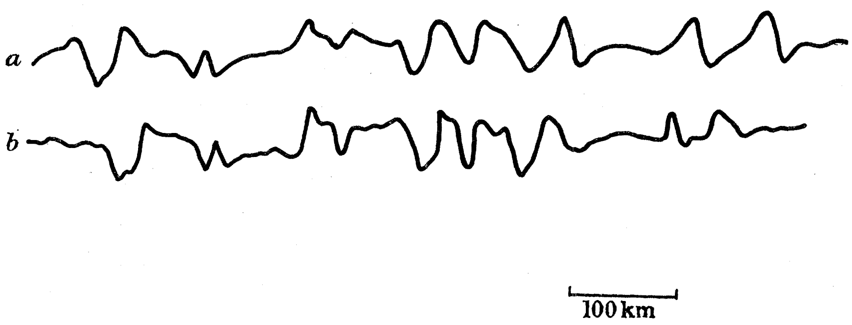

Figure 15. Comparison of a magnetic profile (*a*) in the North Pacific in latitude 41° N with one (*b*) in the South Pacific in latitude 50° S to the east of New Zealand. The section lies about 1500 km from the axis of the ridge and is believed to cover ages from about 60 to 80 My (from Pitman *et al.* 1968).

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The rates of spreading are only determined for the last 3·6 My, which is the period during which the radiometric dates on the continental lavas can be correlated confidently with the magnetic reversals. If the ages of lavas beneath the magnetic stripes on the sea floor could be determined this time scale could be pushed back to perhaps 80 My. Unfortunately the outer parts of the ridge are largely covered by sediment and where igneous rocks are visible they are so decayed as to be unsuitable for dating (see, for example, Matthews 1961); even if they were fresh it is doubtful whether seamounts projecting through the sediments are contemporaneous with the underlying rocks. It may be possible to obtain suitable samples by drilling and to do so is one of the main objects of the JOIDES project (a cooperative drilling project by five universities in the United States). In the meanwhile it is possible to obtain some evidence on the constancy of the spreading rate in the past by comparing sections of the magnetic patterns in different areas. Owing to the effects of differences in latitude and in the strike of the axis of the ridge it is not desirable to compare two magnetic profiles directly. A history of reversals is derived from one profile and the variation of field to be expected along the other is calculated from this and compared with observation; if the rate of spreading has been uniform in both areas, or if the two rates have always been proportional, then the observed curve will agree with the calculated one when the scales are suitably adjusted. Figure 16 shows an example of a comparison of this kind (Phillips 1967), the history of reversals is taken from Pitman & Heirtzler's (1966) analysis of profiles in the South Pacific and the expected magnetic profile 11000 km away at 27° N in the Atlantic is calculated from it. The agreement with observation is almost perfect and removes any lingering doubt that might exist as to the general correctness of the principles on which the calculations are made. A close examination shows that if the scale of the model is adjusted to fit the first three main peaks on each

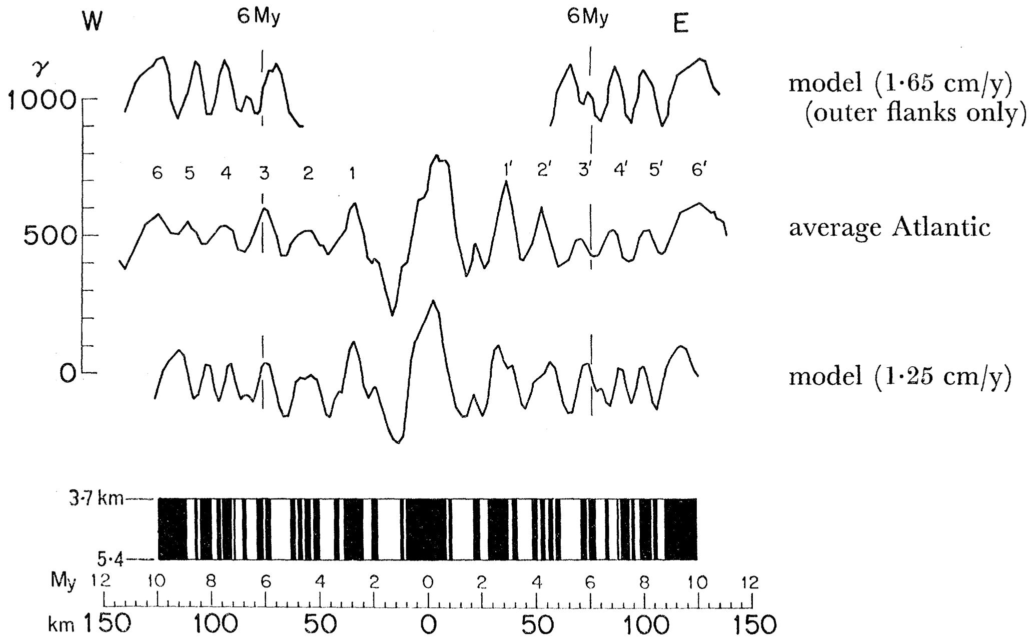

FIGURE 16. Comparison of magnetic profiles in the South Pacific and the Atlantic during the last 10 My (from Phillips 1967).

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side of the central maximum then the peaks further out fall a little nearer the ridge than do the observed ones. This is most naturally interpreted either as a decrease in the rate of spreading in the Atlantic 5 My ago from 1·65 to 1·25 cm/y or as an increase of the rate in the South Pacific from 3·4 to 4·5 cm/y. An example of a much more extended comparison is shown in figure 17; here the distances of corresponding magnetic stripes in the north and south Pacific are compared. Clearly one, or both, rates of spreading have varied in the past; if the spreading rate in the South Pacific has had its present average value (table 3) of 4 cm/y then the figure covers a period of 50 My. Doubtless such comparisons can be made in many areas, a few age determinations will then remove the ambiguities and give a fairly complete history of reversals and of the spreading of the ocean floor all through the Tertiary.

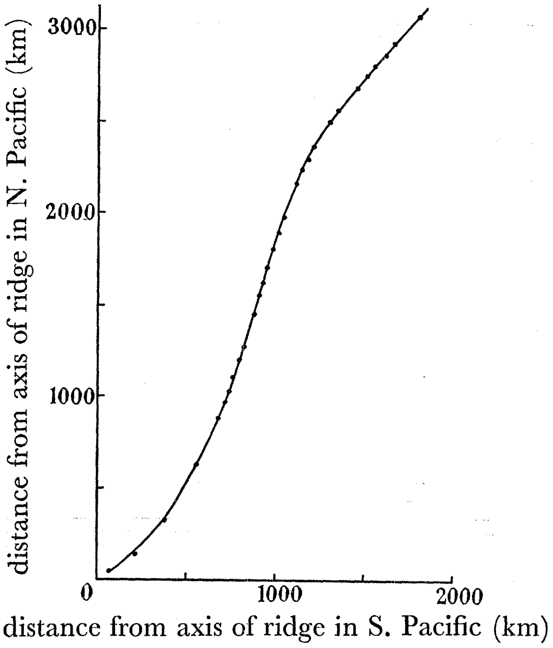

FIGURE 17. Comparison of spreading in the North and South Pacific during the last 50 My (from Pitman *et al.* 1968).

All sufficiently long profiles show a change in character at a distance from the ridge axis corresponding to about 25 My; at this point the anomalies rather suddenly become smoother, of longer wavelength and of greater amplitude than they are nearer the axis (Heirtzler & Le Pichon 1965). The natural explanation is to suppose that at this time there was an increase in the frequency of reversals which has been maintained ever since. In view of the long period during the Permian when the field had a single direction such a change of rate is not improbable and seems more likely than the alternative explanation of a world-wide simultaneous change in the velocity of spreading. A few dates from the outer flanks of the ridge would decide between the two hypotheses.

Around the Atlantic there is a zone extending 100 to 400 km beyond the continental edge in which there is no magnetic pattern parallel to the ridge (Heirtzler & Hayes 1967); it is conceivable that this represents the absence of reversals in the Permian, alternatively it may indicate that this outer rim of the deep Atlantic has a different history from the rest

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or that the magnetized material is here depressed beneath the thick sediments at the foot of the continental slope and has been heated sufficiently to destroy the magnetization.

The rates of spreading in table 3 are compatible with the usual ideas about continental drift, for example, at 38° S the corresponding points on the edges of the continental shelves of South America and Africa are separated by 6400 km; spreading at 1·5 cm/y on both sides of the ridge would produce this separation in 210 My, that is, in the interval since the middle of the Triassic.

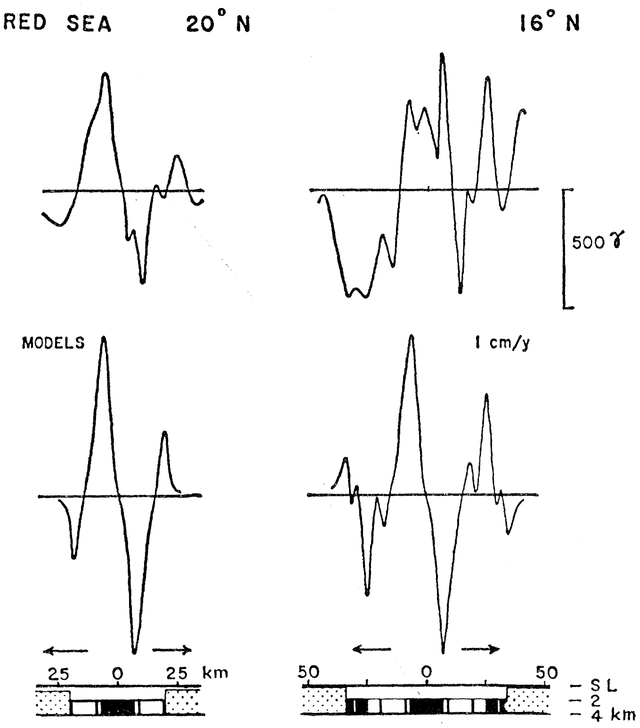

Figure 18. Two magnetic profiles across the Red Sea, the upper curves are the observed profiles, the lower those calculated from the models shown at the bottom (from Vine 1966).

There are several instances where magnetic surveys have revealed symmetrical linear patterns which confirm ideas derived from continental fits and palaeomagnetism. For example, Matthews has found a magnetic pattern parallel to a line bisecting the angle made by the continental edges off the north coast of Spain and the west coast of France. This confirms the suspicion (Carey 1958; Bullard, Everett & Smith 1965), that the Bay of Biscay has been formed by a rotation of Spain.

The Red Sea (figure 18) and the Gulf of Aden have well-marked magnetic patterns which confirm the view, based on other evidence (Girdler 1962, 1967, 1968; Drake & Girdler 1964), that they are embryo oceans which have only started to crack open in the last 3 My, though there may have been a period of stretching and marine transgression prior to this (Vine 1966). There is also a magnetic pattern in the Labrador Sea (Vine 1966) which probably indicates a buried ridge and which should give information about the separation of Greenland and Canada. It would be of great interest if magnetic patterns were found in the landlocked seas, particularly in the Mediterranean, the Black Sea and the Caribbean, the origin of these seas is not clear and may well be different from that of the Atlantic and Indian Oceans.

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The motion of the floor of the whole North Pacific Ocean as a rigid plate has recently been confirmed by a study of the 'first motions' of earthquakes around its edge (McKenzie & Parker 1967).

It is interesting to consider which of the three methods is likely to produce the most detailed history of the reversals of the field, making the most optimistic assumptions. The dating of lavas is unlikely to have an uncertainty of less than 50 ky for very young rocks and 3 % of the age for older ones. Moreover, it is not usually possible to establish the correct sequence for a series of lava flows unless they lie one on top of the other. By itself, therefore, the method is of little use beyond 10 My where the uncertainty is unlikely to be less than 0·3 My. It is, however, the only method that can give absolute dates and it is to be hoped that occasional conspicuous sequences of reversals established by other methods will be recognizable in the lavas all through the Tertiary.

The examination of ocean sediments gives an unambiguous temporal sequence and, at a rate of deposition of 2 cm/ky, might give a resolution as fine as 1000 years over the whole of the Tertiary. The resolution greatly exceeds that of the other methods; it is of the greatest importance to push the technique to its limits (not all results are as clear as those shown in figures 2 and 5) and, if possible, to obtain absolute dates from the cores.

The magnetic pattern on the sea floor can give a resolution limited by the width of the region covered by the dykes on the axis of the ridge. If this is 3 km and the rate of spreading is 5 cm/y, a resolution of 6 ky might be attainable, though this may be over-optimistic due to the overlap of lavas fed by the dykes.

6. Theory of reversals

In addition to their connexion with some of the major problems of geology, the reversals of the Earth's magnetic field pose a difficult physical problem of wide interest in magnetohydrodynamics, geophysics and astrophysics. There are strong reasons for supposing that the Earth's magnetic field is produced by motions in the liquid core which act as a self-exciting dynamo (Rikitake 1966). Such a dynamo, consisting of a simply connected body of fluid, is called a homogeneous dynamo; it is governed by Maxwell's equations and by the equations of hydrodynamics. Certain terms in the full equations are negligible and will be omitted here though their inclusion would cause no difficulty in the present argument. Among these are viscous forces, the displacement current and the field due to the motion of charges. With the omission of these the equations, for an observer on the rotating Earth, are:

$$\begin{gathered}
\operatorname{curl}\mathbf{B}=\mu_0\mathbf{I}=\mu_0 k(\mathbf{E}+\mathbf{v}\times\mathbf{H}),\qquad \operatorname{curl}\mathbf{E}=-\dot{\mathbf{B}},\\
\operatorname{div}\mathbf{B}=0,\qquad \operatorname{div}\mathbf{E}=c^2\mu_0\sigma,\\
\rho\dot{\mathbf{v}}+\rho((\mathbf{v}+\mathbf{\Omega}\times\mathbf{r}).\nabla)(\mathbf{v}+\mathbf{\Omega}\times r)=-\nabla p+\mathbf{I}\times\mathbf{B}+\mathbf{F},\qquad \operatorname{div}(\rho\mathbf{v})=0,
\end{gathered}\tag{1}$$

where $\mathbf{B}$ and $\mathbf{E}$ are the magnetic flux density and electric field, $\mathbf{I}$ is the current, σ the charge density and k the electrical conductivity, all in SI units, $\mathbf{v}$ is the velocity of the fluid relative to axes rotating with the earth, ρ its density, p the pressure, $\mathbf{F}$ the driving force per unit volume (e.g. buoyancy in the Boussinesq approximation), $\mathbf{\Omega}$ the angular velocity of the Earth, $\mathbf{r}$ the vector from the centre of the Earth, c the velocity of light and μ_0 is the permeability of free space ($4\pi\times10^{-7}$). If the electrical conductivity of the mantle is neglected, the boundary

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conditions at the surface of the core are the continuity of **B** and of the tangential components of **E** and the vanishing of the normal components of **I** and **v**. At infinity **B** and **E** vanish at least like $1/r^3$.

Maxwell's equations and the boundary conditions are linear and homogeneous in the fields, currents and charges **E**, **B**, **I** and σ and are therefore unaffected by a reversal of the signs of all these quantities. The hydrodynamic equations contain the field only through the product $\mathbf{I}\times\mathbf{B}$ and are therefore also unaffected by reversal. Thus if a dynamo can maintain a magnetic field it can equally well maintain one that is everywhere equal to the first but in the opposite direction; this applies both to a steady field and to a field that varies with time. The velocity and the applied forces can not in general be reversed, though there are cases in which they can, for example the Herzenberg dynamo.

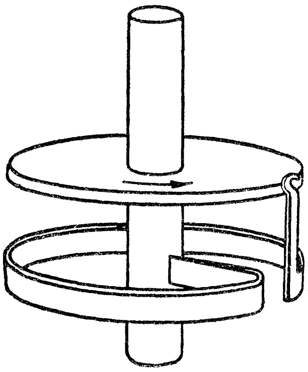

FIGURE 19. A disk dynamo.

This theorem merely demonstrates the existence of reversed solutions; it does not establish that a transition from one state to the other will occur. A man can stand on his head, but it does not follow that he will. The question of whether a homogeneous dynamo will reverse is a very difficult one with which almost no progress has been made. In view of the difficulty of the real problem it has seemed worth while to investigate certain simple systems with a finite number of degrees of freedom that bear some remote resemblance to a homogeneous dynamo. The simplest of these is shown in figure 19, it consists of a conducting disk driven by a constant couple and surrounded by a coil which is connected by brushes to the axle and to the periphery of the disk. If a magnetic field is present a radial e.m.f. is produced in the disk, a current flows in the coil and, if the rotation is in the right direction, the field is maintained. The system has three equilibrium states: one with no current and no field and two with currents and fields in opposite directions and of such magnitudes that the ohmic dissipation of energy equals the work done by the couple. The state with no field and no current is unstable; any disturbance will lead to a permanent current and field. If a shunt is placed across the coil the solutions giving a steady field and current perform the most curious oscillations when disturbed; peaks of current occur, separated by periods with almost no current and, as time passes, all solutions tend to a Dirac comb with ever higher peaks and greater spacing (Bullard 1955*a*). If two of these dynamos are connected together so that the disk of one feeds current to the coil of the other, reversals occur (Rikitake 1958; Allan 1958, 1962; Mathews & Gardner 1963); examples from a digital solution of the differential equations are given in figure 20. Surprisingly, the

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solutions are quite similar to the observed reversals of the Earth's field such as those in figure 2. The field fluctuates many times about its equilibrium value and then suddenly flips over to fluctuate about the reversed equilibrium state. The reversals are of two kinds: sometimes after a reversal the field returns to its original direction after a time of the order of the fluctuation period and sometimes it remains reversed for a much longer time. For most sets of initial conditions the behaviour is quite irregular, a long period near one equilibrium state may be followed by numerous irregularly spaced reversals. The calculations of Mathews & Gardner (1963) were made with an analogue computer and show the solutions to be unstable when both the currents are near zero. It is not impossible that some of the variety of behaviour is not, strictly speaking, a property of the solutions of the equations, but is due to the effects of imperfections in the analogue computer. The single disk dynamo shows a similar instability and will reverse in the presence of small disturbances; it is conceivable that the apparent randomness of the Earth's reversals may be due to a similar instability.

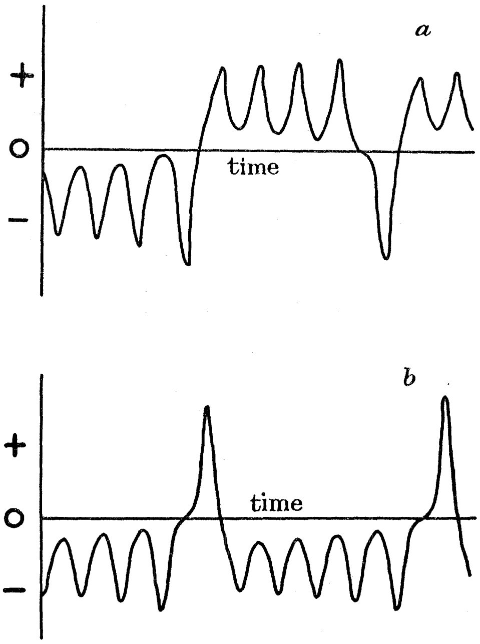

Figure 20. One of the currents in a pair of coupled disk dynamos. In (*a*) the current oscillates about one equilibrium value and then reverses and oscillates about the other. In (*b*), which is an earlier part of the same solution, the reversal only lasts for a short time (from Allan 1962).

It is possible to suggest reasons for the success of the double dynamo model. We know that at the Earth's surface the field is not far from that which would be given by a suitable dipole at the centre of the Earth. If the field is extrapolated downward to the core the dipole field is still the predominant component. We have no direct knowledge of the field within the core but believe that the dipole field is distorted by the motion in such a way that it is reinforced sufficiently to compensate for its natural decay by ohmic dissipation. The possible ways in which this can occur have been catagorized by Bullard & Gellman (1954) by expansion in spherical harmonics and representation in Feyman diagrams (they are not called this in the paper since the similarity was only recently noticed when reading

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Hasselmann (1966)). The interactions of the various possible distortions turn out to be quite complicated and all the plausible systems seem to involve two stages: first the dipole field is distorted by being wound round the axis to give a toroidal field, then this is pushed out into a loop and twisted into a meridian plane to give a dipole field. The velocity field proposed by Bullard & Gellman for doing this is inefficient and there is some suggestion from the work of Braginski (1964) and Tough (1967) that it may not, in fact, work as a dynamo. This defect can probably be remedied. A similar mechanism has been proposed by Babcock (1961) for the Sun; here its plausibility is much increased by the possibility of explaining the laws of sunspot polarity (Bullard 1955*a*). In the Bullard–Gellman dynamo the dipole field produces the toroidal field and the toroidal field produces the dipole field; Babcock suggested that the dipole field might first destroy the toroidal field and then build it up in the opposite direction, the toroidal field would then destroy and reverse the dipole field in the same way. No detailed theory exists in which such a behavior is shown to be a consequence of assumed forces or motions in the Sun. It seems, however, quite likely that some such mechanism is at work and might also occur in the Earth's core (the fields of the Earth and the Sun have been compared by Bullard (1966)). It is interesting that these theories divide the Earth's field into two parts, each of which destroys and creates the other just as the fields of the two halves of the double dynamo do. It is possible that the essential electromagnetic features of the mechanism producing the Earth's field are simulated or realistically caricatured in the double dynamo. On the dynamical side the double dynamo is certainly deficient; in it the applied couples work against electrodynamic forces and any unbalance accelerates the disk; in the Earth the inertia term ($\rho\dot{\mathbf{v}}$ in (1)) is negligible but the Coriolis forces (terms containing the product of $\mathbf{v}$ and $\mathbf{\Omega}$ in (1)) are comparable with the applied forces and the electrodynamic forces. The double dynamo contains no analogue of the Coriolis forces.

In stationary electrical conductors a time of the order $\mu_0 k l^2$ is required for any large change in the field, here k is the electrical conductivity and l is the length in which the field changes by a large fraction of itself. In a fluid system whose parts move with a velocity v there is another time constant l/v which is less than $\mu_0 k l^2$ if

$$v > 1/\mu_0 k l,$$

if k is 3×10^5 ohm^{-1} m^{-1} which is commonly taken as the conductivity of the Earth's core (though Stacey (1967) argues for a value ten times greater) and l is the radius of the core (3400 km), $1/\mu_0 k l$ is 10^{-4} cm/s which is less than the velocities in the core deduced from the westward drift of the field (Bullard, Freedman, Gellman & Nixon 1950). It is therefore quite possible for the Earth's field to change by a large amount in a time much shorter than the time needed for the currents to decay. The physical meaning of this result is that even in a perfect conductor the field at a point can change arbitrarily rapidly since the field is anchored to the fluid and may be carried from place to place or increased by stretching of the lines of force. As a trivial example: suppose currents to be circulating around the equator of a solid metallic sphere. If the sphere is suddenly turned over, the field seen by a fixed observer is reversed. In the sun the changes of the field are very rapid compared to the decay time. A sunspot grows and dies in a few weeks, whereas its electromagnetic decay time would be some years. The main field, both poloidal and toroidal,

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reverses approximately every eleven years, whereas the decay time of a field spread through the whole Sun exceeds 10^9 y. It is therefore quite possible that the Earth's field reverses in less than the decay time of the core, which is about 15 ky, though it is not clear that it actually does so.

7. Causes of spreading of the ocean floor

Belief in spreading of the ocean floor comes fairly directly from the observational evidence and is not dependent on hypotheses about processes occurring deep in the Earth. The occurrence of spreading is, however, a new piece of evidence which must be accommodated in any account of the evolution of the earth. The only plausible cause that has been suggested for it is the occurrence of convection currents in the Earth's mantle; it is not possible here to do more than sketch the leading ideas; many papers on the subject will be found in books edited by Tozer (1967*a*) and Gaskell (1967).

Convection in the mantle has been postulated for a variety of reasons by many people (e.g. Holmes 1931; Meinesz 1952; Hess 1962; Runcorn 1962) and has been declared unnecessary and impossible by others (e.g. Jeffreys 1964; Beloussov 1967; Lyustikh 1967). The main objection has been that the material of the mantle is solid and will therefore have a finite strength and will not distort under small forces. Even if some form of imperfection in elasticity is assumed it is difficult to find a mechanism that will allow thermal convection in the mantle and also account for the numerous other anelastic phenomena, such as the absorption of seismic waves, the slowing of the Earth's rotation and the damping of the Eulerian nutation. The difficulties probably arise from too naïve a view of the solid state. There are many ways in which a solid can depart from Hook's law; which one is important depends on the temperature, pressure and time-scale of the phenomena considered. It is not necessary that the absorption of seismic waves with a period of a few seconds should involve the same mechanism at the atomic level as does convection in the mantle continuing for tens of millions of years. The evidence has recently been reviewed by McKenzie (1968) who concludes that, at the pressures and temperatures occurring in the mantle, diffusion creep will be the predominant mechanism of yield under small, long continued stresses. The rate of strain is then proportional to the shear stress and the material behaves like a viscous liquid. In the lower mantle the resulting viscosity is believed to be too high to allow convection at a significant rate (this is necessary if the non-hydrostatic part of the earth's ellipticity is to be regarded as a fossil relic of a time when the rotation was faster (McKenzie 1966, 1967*a*)). In the upper mantle the viscosity may be of the order of 10^{20} kg m^{-1} s^{-1} which would allow thermal convection and is also compatible with the rise of Scandinavia after the unloading at the end of the ice age. Tozer (1967*b*) has pointed out that, although the viscosity varies rapidly with temperature, there is a certain degree of self regulation; a region of high viscosity moves slowly and gets heated by its own radioactivity until its viscosity is reduced, it is possible that the viscosity may be approximately constant through a layer hundreds of kilometres in thickness, the convective motion may then extend through the whole layer.

There seems to me to have been some misapprehension about the way in which convection is likely to be driven in the mantle. A layer of fluid uniformly heated from below is in equilibrium and, if the temperature gradient does not exceed the adiabatic, the

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equilibrium is stable. It was shown by Benard, Rayleigh and many later authors (e.g. Chandrasekhar 1961) that instability does not set in immediately the adiabatic gradient is exceeded; the gradient must exceed the adiabatic by a finite amount proportional to $1/\kappa\eta$, where κ is the thermal conductivity and η the viscosity, before motion will occur. If this excess gradient is not present viscosity slows down the motion to such an extent that thermal conductivity has time to remove the temperature excess from the incipient rising current. This excess over the adiabatic gradient is very small in large systems and is quite negligible in the Earth. Many authors (e.g. Runcorn 1962) have, however, assumed that this type of calculation will give the size and arrangement of the convection cells. This seems to me unlikely: Rayleigh–Benard convection is the last resort of a system that has nothing else to determine its motion; it is in equilibrium but the equilibrium is unstable and, of all the possible modes of motion, the one that predominates is the one that grows most quickly. In practice Rayleigh–Benard convection is quite hard to observe in the laboratory and is not common in nature. When a layer of fluid is heated from below there are usually horizontal temperature gradients; the system is then not in equilibrium and it is these gradients that determine the motion, the hot parts rise and the colder parts sink, the growth of disturbances from an unstable equilibrium is irrelevant (Allan, Thompson & Weiss 1967). It would be interesting to inquire how large the horizontal gradient must be before it overwhelms the Rayleigh–Benard cells but, so far as I know, this has not been done.

In the Earth there will be deep-seated temperature differences between continents and oceans. The heat flow from the interior of the Earth is very variable from place to place, but on the average is the same under continents and oceans. Since the rocks of the continental crust are several times more radioactive than those of the ocean floor it is to be supposed that the heat reaching the floor of the ocean has come from greater depths than that under the continents. If there were no motion and the thermal conductivity is the same beneath the continents and the oceans then the temperature would be about 200 °C higher at depths of a few hundred kilometres beneath the oceans than it is at the same depth beneath the continents; there would therefore be a tendency for convection currents to rise under the oceans. If motion in fact occurs and the vertical gradient in the mantle is super-adiabatic, the temperature difference will be accentuated by the transport of hot material from the interior to the surface.

Thus it is natural to suppose that the pattern of convection is controlled by the distribution of continents and oceans. If the convection currents are able to move the continents and the distribution of continents determines the convection currents, we have a coupled system whose properties have not been explored. There will, presumably, be a tendency for the continents to congregate over regions of convergence of flow, but the thermal time constants are so long (of the order of 100 My for conduction through 40 km of rock) that more complicated things may happen, for example, a continent might over-run a rising current which continues to rise beneath the continent and causes rifting. It is conceivable that this is at present happening beneath Arizona and Utah and perhaps beneath the African Rift Valleys.

The igneous activity and high heat flow along the axis of the mid-ocean ridges gives some confirmation of the existence of the rising limb of a convection current under the

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ridges and some success has been achieved by McKenzie (1967*b*) in calculating the distribution of heat flow as a function of distance from the axis of the ridge. Many things are left unexplained: why does the convection occur in long lines and not in discrete cells, or is it perhaps in discrete cells distributed along the ridges? Is the existence of discrete cells indicated by the fracture zones which split up the ridge into sections of a few hundred kilometres? Above all, why are the oceanic and continental heat flows the same? If a piece of ocean has a heat flow of 0·05 J m^{-2} s^{-1} and is over-run by a moving continent, then the heat flow through the continent should be the sum of the heat generated in the continental crust, say, 0·05 J m^{-2} s^{-1} and that from the erstwhile ocean floor giving a total of 0·1 J m^{-2} s^{-1} which is twice as great as that assumed for the ocean. Alternatively, if the continent travels on the horizontal limb of a convection current it may retain the same heat flow as it moves, but why should the heat flow from the ocean forming behind it be the same as for the continent? Such arguments are too simple because the time taken for the heat flow through a continent to adjust itself to changes below the Moho is of the order of 100 My. It is not, however, obvious that this provides an escape from the difficulty. Elsasser (1967) has suggested that the convection will automatically even out differences of temperature gradient and heat flow between oceans and continents but the precise way in which this happens is not clear to me from his brief note.

8. The extinction of species

Three independent investigations have shown that the extinction of certain species of marine organisms occurred at about the time of the most recent reversal of the Earth's magnetic field (Harrison & Funnell 1964; Opdyke *et al.* 1966; Hays & Opdyke 1967; Watkins & Goodell 1967*a*). Typical results from Opdyke *et al.* for an Antarctic core are given in figure 21; six species of radiolaria are found to become extinct and three to make their appearance within 30 cm of the polarity change. The column on the right gives the ranges of four faunal zones named Ω, Ψ, X and Φ by Hays (1965). These are based primarily on the sequence of radiolaria in eighty Antarctic deep-sea cores; the boundary between Ψ and X lies near the magnetic transition but the Ω to Ψ boundary does not, the older transition, X to Φ, is rather uncertainly correlated with the Olduvai event.

It is difficult for one who is not a palaeontologist to assess the significance of such results. Species usually do not vanish suddenly, for example, *Discoaster brouweri* which disappeared about 700 ky ago was the last surviving species of a varied assemblage which flourished in the Miocene and became less numerous and less varied during the Pliocene. The species whose disappearance is noted because it coincides with the magnetic transition is one of many about whose relation to transitions we know nothing. The question is, in principle, statistical but data are almost wholly lacking. Even for a single species it is not clear whether the observed discrepancy of 30 cm or so in depth is significant or a result of uncertainty in the determinations; in the Antarctic cores it corresponds to between 50 and 150 ky, which is not small in relation to the time scale of magnetic changes. It is not even certain that the extinction of a single species is simultaneous all over the world.

Whatever doubts there may be about the reality of the correlation between extinction of species and magnetic transitions it is desirable to consider possible explanations. The occasional sudden extinction of large parts of the whole fauna of the Earth is one of the

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great mysteries of natural history and has defied explanation, or rather has attracted a multiplicity of unproved explanations, for over a hundred years (Newell 1963); no opportunity of throwing light on it should be neglected. In fact a correlation between biological change and magnetic reversals was predicted by Uffen (1963, 1965), who suggested that at times when the magnetic field was zero or small, the solar wind and a larger proportion of

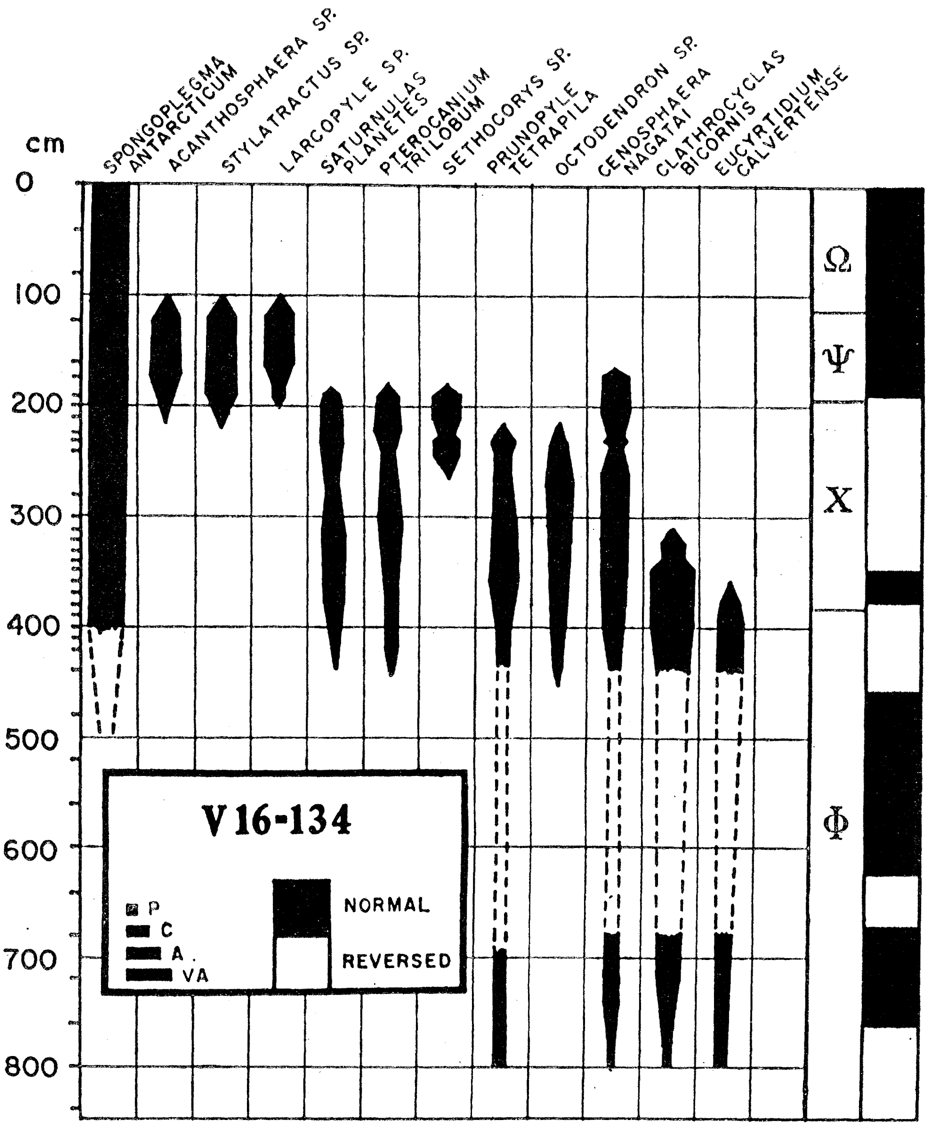

Figure 21. Disappearance of radiolaria near the time of the last reversal of the Earth's magnetic field. The width of the vertical bars indicates the abundance of the species on a scale: P, present; C, common; A, abundant; VA, very abundant. The magnetic stratigraphy is shown in the right-hand column (from Opduke *et al.* 1966).

the cosmic rays would be able to reach the surface of the Earth and also that the particles trapped in the radiation belts would be dumped on the Earth. Uffen supposed that the biological effects of the increase in ionization might affect the course of evolution and bring about the extinction and transformation of species at the time of a magnetic reversal. The verification of the consequences of this hypothesis is striking, but Sagan (1965), Black (1967), Waddington (1967) and Harrison (1968) have pointed out its implausibility. The Earth is

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well protected from ionizing particles by its atmosphere. Even in the absence of a magnetic field the solar wind and particles dumped from the radiation belts would be stopped high in the atmosphere; only high energy cosmic rays can reach the surface, most of the flux being secondary particles generated in the atmosphere. The magnetic field has no effect at the poles but excludes all particles with energy less than 15 GeV at the equator; if the field were turned off the ionization at the Earth's surface near the poles would be unchanged and that at the equator would be increased by about 10 % (the larger effect quoted by Simpson (1966) seems to be incorrect). At the equator the increase would be nullified by descending 1 m deeper into the ocean and is therefore much less than the variations to which the animals are subjected over the 100 m range of depth in which they normally live; over most of this range the whole dose from cosmic rays is unimportant relative to that from the potassium in sea water. In any event, the change in the cosmic rays at the high latitudes of the cores of Opdyke *et al.* is very small.

A number of other effects have been considered by Black (1967). Among these is the ionization due to radioactive atoms produced by cosmic rays. At the top of the atmosphere the softer cosmic rays are present and will be more affected by the field than are those that are able to reach sea level. Thus the production of radioactive isotopes, such as ^{14}C, which can be formed at high altitudes will increase by a much greater factor than does the ionization due to cosmic rays at sea level. For some isotopes this factor is as high as 5 but for ^{14}C, which is the most important, it is 2. The dose from cosmic-ray produced isotopes incorporated in the organism is more important than that from those dissolved in sea water but even at zero field this is less than half that from the potassium in sea water and in the organism, which itself is only 20 % of that from cosmic rays at sea level. It seems impossible that the total ionization within an organism at sea level can be increased by more than 12 % when the Earth's magnetic field is reduced to zero.

Another possibility is that the solar wind might produce ozone in the high atmosphere which would absorb radiation and produce large changes in climate. Black shows that the ozone produced in this way is a very small fraction of that produced by ultraviolet light.

The only possibility of a causal connexion between magnetic reversals and the extinction of species is that ionization in the high atmosphere has an unexpected effect on climate. In spite of our ignorance of many aspects of the general circulation of the atmosphere this seems unlikely, particularly as the time scale of climatic variations seems to be a good deal shorter than the interval between reversals.

Two suggestions have been made of catastrophes that might cause both extinctions and reversals. Glass & Heezen (1967 *a*, *b*) have noticed that the great field of tektites covering Australia, Indonesia and a large part of the Indian Ocean, fell 700 ky ago, at about the time of the last magnetic reversal. They suggest that the fall of the body from which the tektites were formed killed the now extinct radiolaria and gave a jolt to the Earth which disturbed the motion in its core and caused the dynamo to reverse. I find it difficult to believe that a fall of a large meteorite could selectively kill certain species of radiolaria all over the world and yet spare the kangeroos near its point of fall.

Another rather similar suggestion is that the Earth is occasionally visited by showers of magnetic monopoles which kill animals and whose field penetrates to the core and causes the dynamo to reverse (Kolm 1967). The monopoles are supposed to be capable of surviving

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indefinitely after landing; this is necessary to the theory since a magnetic field would take something of the order of 30 y to penetrate the mantle (Bullard 1967*b*). It would also be necessary for the monopoles to be predominantly of one sign. At present the contribution of monopoles to the Earth's field is less than 0·1 % of the whole. If a shower of monopoles occurred there would presumably be a sudden large change in the field at the surface; this has not occurred during the last 400 y. In more remote times the field seems either to have fluctuated about a constant value or to have reversed as is shown in figure 2, one does not get disturbances of all sizes. It is difficult to assess so vague a theory based on the hypothetical properties of particles whose existence is doubtful, but on the whole the hypothesis does not seem either necessary or particularly plausible in relation to the events occurring 700 ky ago. It is, perhaps, more attractive as an explanation of the great extinctions such as those at the end of the Permian and of the Cretaceous.

9. Oxidation and reversed magnetization

The evidence that some rocks are magnetized in a direction opposite to the present field because the field was reversed when they were formed, seems overwhelming; yet there are facts that appear incompatible with this view and for which no convincing explanation can be offered. In order not to interrupt the main argument with inconclusive discussion, this matter has been left till the end.

Table 4. Iron-titanium oxides in order of increasing oxidation

formula	name	O/(Fe+Ti) ratio by atoms
$(Fe, Ti)_3O_4$	titano-magnetite	1·33
$(Fe, Ti)_2O_3$	ilmenite-haematite	1·50
$(Fe, Ti)_3O_5$	pseudo-brookite	1·67

The ferromagnetic minerals in reversely magnetized lavas are more highly oxidized than in normally magnetized ones. This was first shown by Balsey & Buddington (1954, 1958) in the pre-Cambrian rocks of the Adirondacks; it has since been confirmed by several workers in rocks from Mull, Siberia, Iceland, Japan and elsewhere (references to the, in part, rather inaccessible literature are given by Wilson & Watkins (1967); I have also had the advantage of seeing an unpublished manuscript by Professor P. M. S. Blackett). The minerals concerned are mixed oxides of iron and titanium which are shown in table 4 in order of increasing oxidation. The ilmenite first appears as submicroscopic lamellae in the magnetite which, as oxidation proceeds, become larger and more numerous until they replace a large part of the magnetite grains. The degree of oxidation may be estimated by chemical analysis of separated minerals or by a qualitative judgement based on the appearance of polished sections in reflected light (coloured photographs are reproduced in Wilson & Haggerty (1966)). The latter method is more convenient, it enables the rock to be placed in one of five (or sometimes six) classes representing increasing oxidation.

The Columbia Plateau basalts, which are of Miocene age, have been studied in more detail than any other sequence (Wilson & Watkins 1967). Here there are five series each of up to twenty lavas with reversed magnetization which are predominantly, but not exclusively, highly oxidized alternating with five sequences with normal magnetization and a predominantly low degree of oxidation. The correlation of polarity with state of oxidation is

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shown in figure 22; it is striking and beyond doubt statistically significant. The relation, is however, only statistical; there are highly oxidized rocks that are normally magnetized and reversely magnetized ones that are lightly oxidized. Not all lava sequences show as clear a correlation as is shown in figure 22; in fact, Watkins & Haggerty (1967) have shown that the state of oxidation often varies greatly in a single flow being higher in the centre than near the upper or lower margin. When this happens the whole flow has a single polarity. The variations in oxidation appear to be an original feature of the flows and to have been produced during the original solidification and cooling, probably by oxygen derived from the decomposition of water.

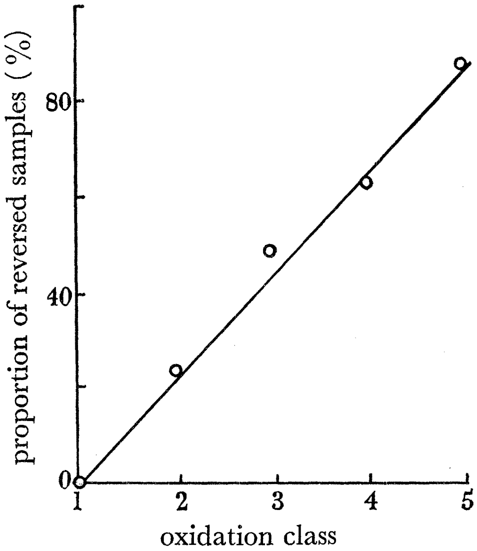

FIGURE 22. Relation between oxidation class and proportion of reversely magnetized samples for the Columbia Plateau Basalts (from Wilson & Watkins 1967).

Several types of explanation of the relation between polarity and oxidation are, in principle, possible; all appear to fall in one of the following classes:

(*a*) The results are due to chance variation and are not statistically significant. This seems demonstrably untrue.

(*b*) The state of oxidation of the rock at the time of cooling determined the direction of magnetization, i.e. the reversely magnetized rocks are self-reversing. This would be the 'natural' explanation if the correlation between polarity and oxidation were all that had to be explained. Against it is the correlation of the polarity of baked and baking rocks (there are several examples of this in the Columbia Plateau basalts), the world-wide consistency of the directions of magnetization during the last 3 My and the agreement between lavas and ocean cores. These latter points do not apply directly to the Columbia Plateau basalts, which are 14 My old. It is very desirable that a detailed study should be made of the state of oxidation of the rocks used to demonstrate the occurrence of the last reversal 0·7 My ago.

(*c*) The field at the time of cooling determined both the polarity and the state of oxidation. The state of oxidation of a lava is determined primarily by its chemical composition, the amount of water present and the rate of cooling. The presence of a magnetic field could have some effect through terms in the free energy proportional to MH where M is the

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magnetic moment of an oxygen molecule (3×10^{-27} J/G) and H is the Earth's field (0·4 G). The corresponding temperature, MH/k, where k is the Boltzmann constant, is 10^{-4} °K. This is negligible compared to the temperature of the lava, but even if it had been larger it would not have produced the required effect. What is wanted is not merely an effect of field on oxidation, but a differential effect depending on the relation of the field to the rotation of the Earth. Such terms no doubt exist but they will be many orders of magnitude smaller than the direct effect of the field and certainly cannot play any appreciable part in the oxidation of the lavas. Indirect effects, such as an effect of field direction on the weather and the weather on the oxidation, seem most implausible, though it is impossible to demonstrate that none can exist.

(*d*) It might be that the field direction and the oxidation had a common cause. For example, reversal of the earth's dynamo might require a redistribution of motions in the core and this might affect motions in the mantle and the chemistry of lavas. The slowness of the mantle motions makes this implausible, but it would be interesting to know if the brief Jaramillo magnetic event is associated with oxidation changes.

If the reversals were precipitated by catastrophes, such as those mentioned in §8, it might be imagined that these also affected the oxidation of rocks. It is, however, difficult to see how the effect could continue through a period of hundreds of thousands of years after the catastrophe.

(*e*) There might be some systematic effect in the selection of samples. The rocks used for polarity determination are a stringently selected class, altered rocks and magnetically unstable rocks are avoided. It is easy to imagine that the more oxidized rocks are preferentially collected, since they are more stable magnetically, but it is difficult to see why highly oxidized rocks that are reversely magnetized should be collected in preference to similar rocks that are normally magnetized.

(*f*) Oxidized rocks differ in their magnetic properties from less oxidized ones. They have a higher coercive force and are more difficult to demagnetize. If a proportion of the lightly oxidized rocks were magnetically unstable they would become magnetized in the direction of the present, 'normal', field and a correlation between polarity and oxidation would be produced. This, at first sight attractive theory, was proposed by Larson & Strangway (1966) who found no correlation between polarity and oxidation when unstable samples were excluded. Wilson & Watkins (1967), on the other hand, find the correlation shown in figure 22 after removing unstable components of magnetization by a.c. fields of up to 800 G. It might be suggested that some lightly oxidized rocks that pass laboratory tests for stability may yet be unstable when subjected to numerous reversals at long intervals of time as the Columbia Plateau basalts have been. Even this hypothesis will not explain all the facts: in particular, it cannot explain the rarity of highly oxidized, normally magnetized rocks among the Columbia Plateau basalts. Worse still, there exist basalts of Carboniferous age at Kinghorn in Scotland, which show a correlation of polarity with oxidation, but for which both the reversed and normal directions make a large angle with the present field (Wilson 1966). Instability of these rocks in the present field would not turn reversed into normal polarity. The case is not as clear as could be wished since the correlation appears only after large unstable components of magnetization have been removed; in their natural state the rocks are magnetized almost at random (Wilson & Everitt 1963).

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None of the proposed explanations is able to explain all the facts, and the correlation of oxidation and magnetic polarity may be seen as one of the major unsolved problems of Earth science. It is probable that things are more complicated than we think and that no one hypothesis can explain all the facts. Perhaps the phenomenon does not occur for rocks of all ages. The most striking examples are for rocks of Eocene and Miocene age. Eocene and Oligocene rocks are predominantly reversely magnetized, Storetvedt (1968) has suggested that the majority of the normally magnetized ones are relatively unstable lightly oxidized ones which have been reversed by subsequent baking in a normal field; baking in a reversed field would produce no change. There is no reason to suppose that this has occurred to the Columbia Plateau Basalts or that the field was predominantly reversed when they were formed in the Miocene. Perhaps the most urgent need is for a study of the state of oxidation of lavas over the period for which good dates and detailed magnetic evidence exist, in particular, for the last million years. Have any highly oxidized, reversed lavas been formed during the last 0·7 My? Are the rocks from the Jaramillo event lightly oxidized compared to those above and below? Do intrusive rocks show a correlation between polarity and oxidation? It is also important to examine the magnetic minerals from ocean sediments; do they show a correlation between polarity and oxidation?

10. Conclusion

The lecture on which this paper is based was given in June 1967; it was a well chosen time, the threefold story of the reversals of the field had just become clear and could be easily and elegantly set out. In the few months needed to write the paper there has been an avalanche of new results which has revealed many discrepancies and many matters needing elucidation; the usual chaos of the Earth sciences is clearly about to be re-established at a higher level of understanding. We can now see many particular facts in the light of a global theory and realize that they are anomalous, whereas previously they appeared merely as isolated facts. The world-wide nature of the reversals can tie together the spreading of the ocean floor and the volcanic and sedimentary history of the last 50 My with a detail never before approached. It is not surprising that ambiguities, difficulties and contradictions are emerging.

References

Allan, D. W. 1958 Reversals of the earth's magnetic field. *Nature, Lond.* **182**, 469–471.

Allan, D. W. 1962 On the behaviour of systems of coupled dynamos. *Proc. Camb. Phil. Soc.* **58**, 671–693.

Allan, D. W., Thompson, W. B. & Weiss, N. O. 1967 Convection in the earth's mantle. *Mantles of the earth and terrestrial planets* (ed. S. K. Runcorn), pp. 507–512. London: Interscience.

Babcock, H. W. 1961 The topology of the sun's magnetic field and the 22-year cycle. *Astrophys. J.* **133**, 572–587.

Balsley, J. R. & Buddington, A. F. 1954 Correlation of reverse remanent magnetism and negative anomalies with certain minerals. *J. Geomagn. Geoelectr., Kyoto* **6**, 176–181.

Balsley, J. R. & Buddington, A. F. 1958 Iron-titanium oxide minerals, rocks and aeromagnetic anomalies of the Adirondack area, New York. *Econ. Geol.* **53**, 777–805.

Beloussov, V. V. 1967 Against continental drift. *Sci. J.* (Jan.), pp. 56–61.

Berggren, W. A., Phillips, J. D., Bertels, A. & Wall, D. 1967 Late Pliocene–Pleistocene stratigraphy in deep sea cores from the south-central North Atlantic. *Nature, Lond.* **216**, 253–255.

Downloaded from rsta.royalsocietypublishing.org

Black, D. I. 1967 Cosmic ray effects and faunal extinctions at geomagnetic field reversals. *Earth Planet. Sci. Lett.* **3**, 225–236.

Blackett, P. M. S. 1962 On distinguishing self-reversed from field-reversed rocks. *J. Phys. Soc. Japan* **17** (suppl. B 1), 699–705.

Bowin, C. O. & Vogt, P. R. 1966 Magnetic lineations between Carlsberg Ridge and Seychelles Bank, Indian Ocean. *J. Geophys. Res.* **71**, 2625–2630.

Braginskiĭ, S. I. 1964 O samovozvuzhdenii magnitnogo polya pri dvizhenii khorosho provodiashcheĭ zhidkosti. *Zh. éksp. teor. Fiz.* **47**, 1084–1098.

Bruhnes, B. 1906 Recherches sur le direction d'aimantation des roches volcaniques. *J. Phys. Radium, Paris* (4) **5**, 705–724.

Bucha, V. 1967 Archaeomagnetic and palaeomagnetic study of the magnetic field of the earth in the past 600,000 years. *Nature, Lond.* **213**, 1005–1007.

Budinger, T. F. & Enbysk, B. J. 1967 Late Tertiary date from the East Pacific Rise. *J. geophys. Res.* **72**, 2271–2273.

Bullard, E. C. 1955*a* The stability of a homopolar dynamo. *Proc. Camb. Phil. Soc.* **51**, 744–760.

Bullard, E. C. 1955*b* The magnetic fields of sunspots. *Vistas in astronomy* (ed. A. Beer), pp. 685–691. New York: Pergamon Press.

Bullard, E. C. 1966 Solar and terrestrial dynamos. *Pubblicazione del comitato nazionale per le manifestazione celebrative del IV centario della nascita di Galileo Galilei*, Vol. 2, Tomo 4, 278–283. Florence: G. Barbèra.

Bullard, E. C. 1967*a* The removal of trend from magnetic surveys. *Earth Planet. Sci. Lett.* 2, 293–300.

Bullard, E. C. 1967*b* Electromagnetic induction in the earth. *Q. Jl R. Astr. Soc.* **8**, 143–160.

Bullard, E. C. & Gellman, H. 1954 Homogeneous dynamos and terrestrial magnetism. *Phil. Trans.* A, **247**, 213–278.

Bullard, E., Everett, J. E. & Smith, A. G. 1965 The fit of the continents around the Atlantic. *Phil. Trans.* A, **258**, 41–51.

Bullard, E. C., Freedman, C., Gellman, H. & Nixon, J. 1950 The westward drift of the earth's magnetic field. *Phil. Trans.* A, 243, 67–92.

Burckle, L. H., Ewing, J., Saito, T. & Leyden, R. 1967 Tertiary sediment from the East Pacific Rise. *Science, N.Y.* **157**, 537–540.

Cann, J. R. & Vine, F. J. 1966 An area of the crest of the Carlsberg Ridge: petrology and magnetic survey. *Phil. Trans.* A, **259**, 198–217.

Carey, S. W. 1958 *Continental drift, a symposium*. Hobart.

Carmichael, C. M. 1961 The magnetic properties of ilmenite-haematite crystals. *Proc. R. Soc.* A, **263**, 508–530.

Chamalaun, F. H. & McDougall, I. 1966 Dating geomagnetic polarity epochs in Réunion. *Nature, Lond.* **210**, 1212–1214.

Chandrasekhar, S. 1961 *Hydrodynamic and hydromagnetic stability*. Oxford: Clarendon Press.

Chevalier, R. 1925 L'aimantation des laves de l'Etna et l'orientation du champ terrestre en Sicile du XII$^{\mathrm{e}}$ au XVII$^{\mathrm{e}}$ siecle. *Annls. Phys.* (10), **4**, 5–162.

Cox, A. & Dalrymple, G. B. 1966 Palaeomagnetism and potassium-argon ages of some volcanic rocks from the Galapagos Islands. *Nature, Lond.* **209**, 776–777.

Cox, A. & Dalrymple, G. B. 1967*a* Statistical analysis of geomagnetic reversal data and the precision of potassium-argon dating. *J. Geophys. Res.* **72**, 2603–2614.

Cox, A. & Dalrymple, G. B. 1967*b* Geomagnetic polarity epochs: Nunivac Island, Alaska. *Earth Planet. Sci. Lett.* **3**, 173–177.

Cox, A., Dalrymple, G. B. & Doell, R. B. 1967 Reversals of the earth's magnetic field. *Scient. Am.*, **216**, 44–54.

Cox, A., Doell, R. R. & Dalrymple, G. B. 1963*a* Geomagnetic polarity epochs and Pleistocene geochronology. *Nature, Lond.* **198**, 1049–1051.

Downloaded from rsta.royalsocietypublishing.org

Cox, A., Doell, R. R. & Dalrymple, G. B. 1963*b* Geomagnetic polarity epochs: Sierra Nevada II. *Science, N.Y.* **142**, 382–385.

Cox, A., Doell, R. R. & Dalrymple, G. B. 1964*a* Geomagnetic polarity epochs: a lesson in correlation. *Science, N.Y.* **143**, 351–352.

Cox, A., Doell, R. R. & Dalrymple, G. B. 1964*b* Reversals of the earth's magnetic field. *Science, N.Y.* **144**, 1537–1543.

Cox, A., Doell, R. R. & Dalrymple, G. B. 1965 Quaternary paleomagnetic stratigraphy. *Quaternary stratigraphy of the United States* (ed. H. E. Wright and D. G. Frey), pp. 817–830. Princeton University Press.

Cox, A., Hopkins, D. M. & Dalrymple, G. B. 1966 Geomagnetic polarity epochs: Pribilof Islands, Alaska. *Bull. Geol. Soc. Am.* **77**, 883–910.

Creer, K. M. 1958 Preliminary palaeomagnetic measurements from South America. *Annls. Géophys.* **14**, 373–390.

Dalrymple, G. B., Cox, A. & Doell, R. R. 1965 Potassium-argon age and paleomagnetism of the Bishop Tuff, California. *Bull. geol. Soc. Am.* **76**, 665–674.

Dalrymple, G. B., Cox, A., Doell, R. R. & Grommé, C. S. 1967 Pliocene geomagnetic polarity epochs. *Earth Planet. Sci. Lett.* **2**, 163–173.

Demenitskaya, R. M. 1967 *Kora i mantiya zemli.* Moscow: Izdatel'stvo Nedra.

Dickson, G. O. & Foster, J. H. 1966 The magnetic stratigraphy of a deep sea core from the North Pacific Ocean. *Earth Planet. Sci. Lett.* **1**, 458–462.

Dickson, G. O., Pitman, W. C. & Heirtzler, J. R. 1968 Magnetic anomalies in the South Atlantic and ocean floor spreading. *J. Geophys. Res.* **73**, 2087–2100.

Dietz, R. S. 1961 Continent and ocean basin evolution by spreading of the sea floor. *Nature, Lond.* **190**, 854–857.

Doell, R. R. & Dalrymple, G. B. 1966 Geomagnetic polarity epochs—a new polarity event and the age of the Brunhes–Matuyama boundary. *Science, N.Y.* **152**, 1060–1061.

Doell, R. R., Dalrymple, G. B. & Cox, A. 1966 Geomagnetic polarity epochs; Sierra Nevada data 3. *J. Geophys. Res.* **71**, 531–541.

Drake, C. L. & Girdler, R. W. 1964 A geophysical study of the Red Sea. *Geophys. J.* **8**, 473–495.

Dymond, J. R. 1966 Potassium-argon geochronology of deep-sea sediments. *Science, N.Y.* **152**, 1239–1241.

Elsasser, W. M. 1967 Interpretation of heat flow equality. *J. Geophys. Res.* **72**, 4768–4770.

Elvers, D. J., Mathewson, C. C., Kohler, R. E. & Moses, R. L. 1967 Systematic ocean surveys by the USC and GSS Pioneer 1961–1963. *Coast and Geodetic Survey Operational Data Report*, C & GSDR–1.

Emery, K. O. & Dietz, R. S. 1941 Gravity coring instrument and mechanics of sediment coring. *Bull. Geol. Soc. Am.* **52**, 1685–1714.

Evans, P. 1969 Towards a Pleistocene time-scale. *Q. Jl Geol. Soc. Lond.* (In the press.)

Everitt, C. W. F. 1962 Self-reversal of magnetisation in a shale containing Pyrrhotite. *Phil. Mag.* (5), **7**, 831–842.

Ewing, M. & Ewing, J. I. 1967*a* Deep sea sediments in relation to island arcs and mid–ocean ridges. *Trans. Am. Geophys. Un.* **48**, 216 (abstract).

Ewing, M. & Ewing, J. I. 1967*b* Sediment distribution on the mid-ocean ridges with respect to spreading of the sea floor. *Science, N.Y.* **156**, 1590–1592.

Ewing, M., Le Pichon, X. & Ewing, J. 1966 Crustal structure of the Atlantic Ridge. *J. Geophys. Res.* **71**, 1611–1636.

Funnell, B. M. 1968 Pre-Quaternary occurrences of micro-fossils in the oceans. *Micropalaeontology of Oceans* (SCOR Symposium Volume). Cambridge University Press (in the Press).

Gaskell, T. F. (editor) 1967 *The earth's mantle.* London: Academic Press.

Gelletich, H. 1937 Über magnetitführende eruptive Gänge und Gangsysteme in mittleren Teil des südlichen Transvaals. *Beitr. angew. Geophys.* **6**, 337–406.

Downloaded from rsta.royalsocietypublishing.org

Girdler, R. W. 1959 Possible reversals of the earth's magnetic field in the Jurassic period. *Nature, Lond.* **184**, 540–541.

Girdler, R. W. 1962 Initiation of continental drift. *Nature, Lond.* **194**, 521–524.

Girdler, R. W. 1967 The role of translational and rotational movements in the formation of the Red Sea and Gulf of Aden. In *The world rift system. Geol. Surv. Can. Paper*, 66–14, 65–77.

Girdler, R. W. 1968 Drifting and rifting in Africa. *Nature, Lond.* **217**, 1102–1106.

Glass, B. P. & Heezen, B. C. 1967*a* Tektites and geomagnetic reversals. *Nature, Lond.* **214**, 372–374.

Glass, B. P. & Heezen, B. C. 1967*b* Tektites and geomagnetic reversals. *Scient. Am.* **217**, 32–38.

Goldberg, E. D. & Koide, M. 1962 Geochronological studies of deep sea sediments by the ionium/thorium method. *Geochim. cosmochim. Acta* **26**, 417–450.

Goodell, H. G. & Watkins, N. D. 1968 The paleomagnetic stratigraphy of the Southern Ocean: 20° west to 160° east longitude. *Deep Sea Res.* **15**, 89–112.

Grim, P. J. & Erickson, B. H. 1967 Marine magnetic anomalies and fracture zones south of the Aleutian Trench. *Geol. Soc. Am. Abstracts*, p. 84.

Gromme, C. S. & Hay, R. L. 1963 Magnetisation of basalt of Bed I, Olduvai Gorge, Tanganyika. *Nature, Lond.* **200**, 560–561.

Harrison, C. G. A. 1966 The paleomagnetism of deep sea sediments. *J. Geophys. Res.* **71**, 3033–3043.

Harrison, C. G. A. 1968 Evolutionary processes and reversals of the earth's magnetic field. *Nature, Lond.* **217**, 46–47.

Harrison, C. G. A. & Funnell, B. M. 1964 Relationship of palaeomagnetic reversals and micropalaeontology in two late Caenozoic cores from the Pacific Ocean. *Nature, Lond.* **204**, 566.

Harrison, C. G. A. & Somayajulu, B. L. K. 1966 Behaviour of the earth's magnetic field during a reversal. *Nature, Lond.* **212**, 1193–1195.

Hasselmann, K. 1966 Feynman diagrams and interaction rules of wave-wave scattering processes. *Rev. Geophys.* **4**, 1–32.

Hays, J. D. 1965 Radiolaria and late Tertiary and Quaternary history of Antarctic seas. In *Biology of the Antarctic seas*, II, Vol. 5. *Antarctic Res. Ser. Am. geophys. Un. Publ.* no. 1297.

Hays, J. D. & Opdyke, N. D. 1967 Antarctic radiolaria, magnetic reversals and climatic change. *Science, N.Y.* **158**, 1001–1011.

Heirtzler, J. R. 1967 Marine magnetic anomalies and a moving ocean floor. *Trans. Am. Geophys. Un.* **48**, 216 (abstract).

Heirtzler, J. R. & Hayes, D. E. 1967 Magnetic boundaries in the North Atlantic Ocean. *Science, N.Y.* **157**, 185–187.

Heirtzler, J. R. & Le Pichon, X. 1965 Crustal structure of the mid-ocean ridges 3. Magnetic anomalies over the mid-Atlantic ridge. *J. Geophys. Res.* **70**, 4013–4033.

Heirtzler, J. R., Le Pichon, X. & Baron, J. G. 1966 Magnetic anomalies over the Reykjanes Ridge. *Deep Sea Res.* **13**, 427–443.

Heirtzler, J. R., Dickson, G. O., Herron, E. M., Pitman, W. C. & Le Pichon, X. 1968 Marine magnetic anomalies, geomagnetic field reversals and motions of the ocean floor and continents. *J. Geophys. Res.* **73**, 2119–2136.

Hess, H. H. 1962 History of ocean basins. *Petrological studies: a volume in honor of A. F. Buddington* (ed. A. E. J. Engel, H. L. James and B. F. Leonard), pp. 559–620. New York: Geol. Soc. Am.

Hess, H. H. 1965 Mid-oceanic ridges and tectonics of the sea-floor. *Submarine geology and geophysics* (ed. W. F. Whittard and R. Bradshaw), pp. 317–333. London: Butterworths.

Holmes, A. 1931 Radioactivity and earth movements. *Trans. Geol. Soc. Glasg.* **18**, 559–606.

Hospers, J. 1951 Remanant magnetism of rocks and the history of the geomagnetic field. *Nature, Lond.* **168**, 1111–1112.

Hospers, J. 1953*a* Reversals of the main geomagnetic field, I. *Proc. Ned. Akad. Wet.* B, **56**, 467–476.

Hospers, J. 1953*b* Reversals of the main geomagnetic field, II. *Proc. Ned. Akad. Wet.* B, **56**, 477–491.

Hospers, J. 1954 Reversals of the main geomagnetic field, III. *Proc. Ned. Akad. Wet.* B, **57**, 112–121.

Downloaded from rsta.royalsocietypublishing.org

Huene, R. van, Scholl, D. W. & Ridlan, J. B. 1967 Sediment distribution and deformation in the Peru–Chile trench and the adjacent continental shelf. *Geol. Soc. Am. Abstracts*, 229 (abstract).

Irving, E. 1964 *Palaeomagnetism.* New York: Wiley.

Jeffreys, H. 1964 How soft is the earth? *Q. Jl R. Astr. Soc.* **5**, 10–22.

Johnson, E. A., Murphy, T. & Torreson, O. W. 1948 Pre-history of the earth's magnetic field. *Terr. Magn. Atmos. Elect.* **53**, 349–372.

Keen, M. J. 1960 Magnetisation of sediment cores from the eastern North Atlantic Ocean. *Nature, Lond.* **187**, 220–222.

Keen, M. J. 1963 The magnetisation of sediment cores from the eastern basin of the North Atlantic Ocean. *Deep Sea Res.* **10**, 607–622.

Khramov, A. N. 1957 O paleomagnetizme kak osnove novogo metoda korrelyatsii i rascheleneniya osadochnykh tolshch. *Dokl. Akad. Nauk SSSR* **112**, 849–859.

Khramov, A. N. 1958 *Paleomagnitnaya korrelyachiya osadochnykh tolshch.* Leningrad: Gostoptechizdat (translated as *Palaeomagnetism and stratigraphic correlations* by the Australian National University, Canberra).

Koenigsberger, J. K. 1938 Natural residual magnetism of eruptive rocks. *Terr. Magn. Atmos. Elect.* **43**, 119–130, 299–320.

Kolm, H. H. 1967 Search for magnetic monopoles in deep-sea sediment. *Phys. Today*, **20**, 69–70.

Krause, D. C. 1967 Magnetic evidence for western Caribbean Basin origin by late cretaceous spreading. *Trans. Am. Geophys. Un.* **48**, 133 (abstract).

Kullenberg, B. 1947 The piston core sampler. *Svenska hydrogr.-biol. Kommn. Skr.* (ser. 3, Hydrog.), 1, no. 2, 1–46.

Larson, E. E. & Strangway, D. W. 1966 Magnetic polarity and igneous petrology. *Nature, Lond.* **212**, 756–757.

Le Pichon, X. & Heirtzler, J. R. 1968 Magnetic anomalies in the Indian Ocean and sea floor spreading. *J. Geophys. Res.* **73**, 2101–2117.

Lyustikh, E. N. 1967 Criticism of hypothesis of convection and continental drift. *Geophys. J. R. Astr. Soc.* **14**, 347–352.

McDougall, I. & Chamalaun, F. H. 1966 Geomagnetic polarity scale of time. *Nature, Lond.* **212**, 1415–1418.

McDougall, I. & Tarling, D. H. 1963 Dating of polarity zones in the Hawaiian Islands. *Nature, Lond.* **200**, 54–56.

McDougall, I. & Tarling, D. H. 1964 Dating of geomagnetic polarity zones. *Nature, Lond.* **202**, 171–172.

McDougall, I. & Wensink, H. 1966 Paleomagnetism and geochronology of the Pliocene–Pleistocene lavas in Iceland. *Earth Planet. Sci. Lett.* **1**, 232–236.

McKenzie, D. P. 1966 The viscosity of the lower mantle. *J. Geophys. Res.* **71**, 3995–4010.

McKenzie, D. P. 1967*a* The viscosity of the mantle. *Geophys. J. R. Astr. Soc.* **14**, 297–305.

McKenzie, D. P. 1967*b* Some remarks on heat flow and gravity anomalies. *J. Geophys. Res.* **72**, 6261–6273.

McKenzie, D. P. 1968 The geophysical importance of high temperature creep. NASA conference on the history of the earth's crust (in the Press).

McKenzie, D. P. & Parker, R. L. 1967 The North Pacific: an example of tectonics on a sphere. *Nature, Lond.* **216**, 1276–1280.

McNish, A. G. & Johnson, E. A. 1938 Magnetisation of unmetamorphosed varves and marine sediments. *Terr. Magn Atmos. Elect.* **43**, 401–407.

Mason, R. G. 1958 A magnetic survey off the west coast of the United States between latitudes 32° and 36° N, longitudes 121° and 128° W. *Geophys. J. R. Astr. Soc.* **1**, 320–329.

Mason, R. G. & Raff, A. D. 1961 A magnetic survey off the west coast of North America, 32° N to 42° N. *Bull. Geol. Soc. Am.* **72**, 1259–1265.

Downloaded from rsta.royalsocietypublishing.org

Mathews, J. H. & Gardner, W. K. 1963 Field reversals of 'paleomagnetic' type in coupled disk dynamos. *NRL Rep.* no. 5886.

Matthews, D. H. 1961 Lavas from an abyssal hill on the floor of the North Atlantic Ocean. *Nature, Lond.* **190**, 158–159.

Matthews, D. H. & Bath, J. 1967 Formation of magnetic anomaly pattern of mid-Atlantic Ridge. *Geophys. J. R. Astr. Soc.* **13**, 349–357.

Matthews, D. H., Vine, F. J. & Cann, J. R. 1965 Geology of an area of the Carlsberg Ridge, Indian Ocean. *Bull. Geol. Soc. Am.* **76**, 675–682.

Matthews, D. H., Williams, C. & Laughton, A. S. 1967 Mid-ocean ridge in the mouth of the Gulf of Aden. *Nature, Lond.* **215**, 1052–1053.

Matuyama, M. 1929 On the direction of magnetisation of basalt in Japan, Tyôsen and Manchuria. *Proc. Imp. Acad. Japan* **5**, 203–205.

Meinesz, F. A. V. 1952 Convection-currents in the earth and the origin of the continents. *Proc. K. Ned. Akad. Wet.* B, **55**, 427–553.

Menard, H. W. 1964 *Marine geology of the Pacific.* New York: McGraw-Hill.

Menard, H. W. 1967 Sea floor spreading, topography, and the second layer. *Science, N.Y.* **157**, 923–924.

Mercanton, M. P. 1910 État magnétique des diabases de l'Isfjord au Spitzberg. *C. r. hebd. Séanc. Acad. Sci., Paris* **151**, 1092–1094.

Mudie, J. D. & Harrison, C. G. A. 1967 Deep tow profiles across Mason-Raff lineations. *Trans. Am. Geophys. Un.* **48**, 133 (abstract).

Nagata, T. 1951 Reverse thermo remanant magnetism. *Nature, Lond.* **169**, 704–705.

Nagata, T. 1961 *Rock magnetism.* Tokyo: Maruzen.

Nagata, T., Uyeda, S. & Akimoto, S. 1952 Self-reversal of thermo-remanant magnetisation of igneous rocks. *J. Geomagn. Geoelect., Kyoto* **4**, 22–38.

Néel, L. 1951 L'inversion de l'aimantation permanente des roches. *Annls Géophys.* **7**, 90–102.

Newell, N. D. 1963 Crises in the history of life. *Scient. Am.* **208**, 76–92.

Ninkovich, D., Opdyke, N., Heezen, B. C. & Foster, J. H. 1966 Paleomagnetic stratigraphy, rates of deposition and tephrochronology in North Pacific deep-sea sediments. *Earth Planet. Sci. Lett.* **1**, 476–492.

Opdyke, N. D. & Foster, J. H. 1967 Reversals of the earth's magnetic field. *Sci. J.* (Sept.), pp. 56–61.

Opdyke, N. D., Glass, B., Hays, J. D. & Foster, J. 1966 Palaeomagnetic study of Antarctic Deep-Sea cores. *Science, N.Y.* **154**, 349–357.

Ozima, M. & Ozima, M. 1967 Self-reversal of remanent magnetisation in some dredged submarine basalts. *Earth Planet. Sci. Lett.* **3**, 213–215.

Ozima, M., Ozima, M. & Kaneoka, I. 1968 Potassium-argon ages and magnetic properties of some dredged submarine basalts and their geophysical implications. *J. Geophys. Res.* **73**, 711–723.

Ozima, M., Kono, M., Kaneoka, I., Kinoshita, H., Kobayashi, K., Nagata, T., Larsen, E. E. & Strangway, D. 1967 Paleomagnetic and potassium-argon ages of some volcanic rocks from the Rio Grande Gorge, New Mexico. *J. Geophys. Res.* **72**, 2615–2621.

Peter, G. 1966 Magnetic anomalies and fracture pattern in the northeast Pacific Ocean. *J. Geophys. Res.* **71**, 5365–5374.

Peter, G. & Stewart, H. B. 1965 Ocean surveys: the systematic approach. *Nature, Lond.* **206**, 1017–1018.

Phillips, J. D. 1967 Magnetic anomalies over the mid-Atlantic ridge near 27° N. *Science, N.Y.* **157**, 920–923.

Pitman, W. C. & Heirtzler, J. R. 1966 Magnetic anomalies over the Pacific-Antarctic ridge. *Science, N.Y.* **154**, 1164–1171.

Pitman, W. C., Herron, E. & Heirtzler, R. 1968 Magnetic anomalies in the Pacific and sea-floor spreading. *J. Geophys. Res.* **73**, 2069–2085.

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Raff, A. D. 1962 Further magnetic measurements along the Murray fault. *J. Geophys. Res.* **67**, 417–418.

Raff, A. D. 1966 Boundaries of an area of very long magnetic anomalies in the northeast Pacific. *J. Geophys. Res.* **71**, 2631–2636.

Raff, A. D. & Mason, R. G. 1961 A magnetic survey off the west coast of North America, 40° N to 52½° N. *Bull. Geol. Soc. Am.* **72**, 1267–1270.

Rassokho, A. I., Senchura, L. I., Demenitskaya, R. M., Karosik, A. M., Kiselev, Yu. G. & Timoshchenko, N. K. 1967 Podvodnyĭ sredinnyĭ Arkticheskiy Khrebet i ego mesto v sisteme khrebtov Severnogo Ledovitogo okeana. *Dokl. Akad. Nauk SSSR* **172**, 659–662.

Rikitake, T. 1958 Oscillations of a system of disc dynamos. *Proc. Camb. Phil. Soc.* **54**, 89–105.

Rikitake, T. 1966 *Electromagnetism and the earth's interior.* Amsterdam: Elsevier.

Ross, D. A. & Riedel, W. R. 1967 Comparison of upper parts of some piston cores with simultaneously collected open-barrel cores. *Deep Sea Res.* **14**, 285–294.

Runcorn, S. K. 1962 Towards a theory of continental drift. *Nature, Lond.* **193**, 311–314.

Sagan, C. 1965 Is the early evolution of life related to the development of the earth's core. *Nature, Lond.* **206**, 448.

Saito, T., Ewing, M. & Burkle, L. H. 1966 Tertiary sediment from the mid-Atlantic ridge. *Science, N.Y.* **151**, 1075–1079.

Schlich, R. & Patriat, P. 1967 Profils magnetiques sur la dorsale 'Indo-Pacifique'. *IUGG Abstracts* **8**, 48 (abstract).

Scholl, D. W., Huene, H. van & Ridlon, J. B. 1967 Deformation of sediments in Peru-Chile trench in relation to possible sea-floor spreading. *Geol. Soc. Am. Abstracts*, p. 196 (abstract).

Simpson, J. F. 1966 Evolutionary pulsations and geomagnetic polarity. *Bull. Geol. Soc. Am.* **77**, 197–203.

Stacey, F. D. 1967 Electrical resistivity of the earth's core. *Earth Planet. Sci. Lett.* **3**, 204–206.

Storetvedt, K. M. 1968 On remagnetisation problems in palaeomagnetism. *Earth Planet. Sci. Lett.* **4**, 107–112.

Suess, E. 1888 *Das Antlitz der Erde*, vol. 2, pt. 3, chap. 4. Vienna: F. Tempsky (translated 1906 by H. B. C. Sollas as *The face of the earth.* Oxford: Clarendon Press).

Sykes, L. R. 1967 Mechanism of earthquakes and nature of faulting on the mid-ocean ridges. *J. Geophys. Res.* **72**, 2131–2153.

Talwani, M., Le Pichon, X. & Heirtzler, J. R. 1965 East Pacific rise: the magnetic pattern and the fracture zones. *Science, N.Y.* **150**, 1109–1115.

Thellier, E. & Thellier, O. 1959 Sur l'intensité du champ magnétique terrestre dans le passé historique et géologique. *Annls Géophys.* **15**, 285–376.

Tough, J. G. 1967 Nearly symmetric dynamos. *Geophys. J. R. Astr. Soc.* **13**, 393–396.

Tozer, D. C. (ed.) 1967*a* The proceedings of the International Upper Mantle Committee Symposium on non-elastic processes in the mantle. *Geophys. J. R. Astr. Soc.* **14**, 1–450.

Tozer, D. C. 1967*b* Some aspects of thermal convection theory for the earth's mantle. *Geophys. J. R. Astr. Soc.* **14**, 395–402.

Uffen, R. J. 1963 Influence of the earth's core on the origin and evolution of life. *Nature, Lond.* **198**, 143–144.

Uffen, R. J. 1965 The evolution of the interior of the earth and its effects on biological evolution. *Upper Mantle Symposium, New Delhi* 1964. IUGS: Copenhagen.

Uyeda, S. 1958 Thermo-remanent magnetism as a medium of palaeomagnetism, with special reference to reverse thermo-remanent magnetism. *Jap. J. Geophys.* **2**, 1–123.

Uyeda, S., Vacquier, V., Yasui, M., Sclater, J., Sato, T., Lawson, J., Watanabe, T., Dixon, F., Silver, E., Fukao, Y., Sudo, K., Nishikawa, M. & Tonaka, T. 1967 Results of geomagnetic survey during the cruise of *R/V Argo* in Western Pacific 1966 and the compilation of magnetic charts of the same area. *Bull. Earthq. Res. Inst.* **45**, 799–814.

Vacquier, V. 1965 Transcurrent faulting in the ocean floor. *Phil. Trans.* A, **258**, 77–81.

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Vacquier, V. & Von Herzen, R. P. 1964 Evidence for connection between heat flow and the mid-Atlantic Ridge magnetic anomaly. *J. Geophys. Res.* **69**, 1093–1101.

Vacquier, V., Raff, A. D. & Warren, R. E. 1961 Horizontal displacements in the floor of the Pacific Ocean. *Bull. Geol. Soc. Am.* **72**, 1251–1258.

Van Zijl, J. S. V., Graham, K. W. & Hales, A. L. 1962*a* The palaeomagnetism of the Stormberg lavas of South Africa. I. Evidence for a genuine reversal of the earth's field in Triassic-Jurassic times. *Geophys. J. R. Astr. Soc.* **7**, 23–39.

Van Zijl, J. S. V., Graham, K. W. T. & Hales, A. L. 1962*b* The palaeomagnetism of the Stormberg lavas, II. The behaviour of the magnetic field during a reversal. *Geophys. J. R. Astr. Soc.* **7**, 169–182.

Vine, F. J. 1966 Spreading of the ocean floor: new evidence. *Science, N.Y.* **154**, 1405–1415.

Vine, F. J. & Matthews, D. H. 1963 Magnetic anomalies over ocean ridges. *Nature, Lond.* **199**, 947–949.

Vine, F. J. & Morgan, W. J. 1967 Simulation of mid-ocean ridge magnetic anomalies using a random injection model. *Geol. Soc. Am. Abstracts* p. 228 (abstract).

Vine, F. J. & Wilson, J. T. 1965 Magnetic anomalies over a young ocean ridge off Vancouver island. *Science, N.Y.* **150**, 485–489.

Vlasov, A. Ya. & Kovalenko, G. V. 1963 Magnetizm perekhodn sloev mezhdu zonami s pryamoĭ obratnoĭ namagnichennosty. *Izv. Akad. Nauk SSSR* (Ser. Geofiz.), pp. 552–560.

Waddington, C. J. 1967 Paleomagnetic field reversals and cosmic radiation. *Science, N.Y.* **158**, 913–915.

Watkins, N. D. 1968 Comments on the interpretation of linear magnetic anomalies. *Geofiz. pura appl.* **69**, 111–123.

Watkins, N. D. & Goodell, H. G. 1967*a* Geomagnetic polarity change and faunal extinction in the Southern Ocean. *Science, N.Y.* **156**, 1083–1087.

Watkins, N. D. & Goodell, H. G. 1967*b* Confirmation of the reality of the Gilsa geomagnetic polarity event. *Earth Planet. Sci. Lett.* **2**, 123–129.

Watkins, N. D. & Goodell, H. G. 1967*c* Inconsistencies resulting from a limited study of magnetic polarity variation in submarine sedimentary cores. *Trans. Am. Geophys. Un.* **48**, 90. (abstract).

Watkins, N. D. & Haggerty, S. E. 1967 Primary oxidation variation and petrogenesis in a single lava. *Contr. Miner. Petr.* **15**, 251–271.

Wilson, J. T. 1965*a* A new class of faults and their bearing on continental drift. *Nature, Lond.* **207**, 343–347.

Wilson, J. T. 1965*b* Submarine fracture zones, aseismic ridges and the International Council of Scientific Unions Line: proposed western margin of the East Pacific Ridge. *Nature, Lond.* **207**, 907–911.

Wilson, J. T. 1965*c* Transform faults, oceanic ridges and magnetic anomalies southwest of Vancouver Island. *Science, N.Y.* **150**, 482–485.

Wilson, R. L. 1962*a* The palaeomagnetism of baked contact rocks and reversals of the earth's magnetic field. *Geophys. J. R. Astr. Soc.* **7**, 194–202.

Wilson, R. L. 1962*b* The palaeomagnetic history of a doubly-baked rock. *Geophys. J. R. Astr. Soc.* **6**, 397–399.

Wilson, R. L. 1966 Further correlations between the petrology and the natural magnetic polarity of basalts. *Geophys. J. R. Astr. Soc.* **10**, 413–420.

Wilson, R. L. & Everitt, C. W. F. 1963 Thermal demagnetisation of some Carboniferous lavas for palaeomagnetic purposes. *Geophys. J. R. Astr. Soc.* **8**, 149–164.

Wilson, R. L. & Haggerty, S. E. 1966 Reversals of the earth's magnetic field. *Endeavour* **25**, 104–109.

Wilson, R. L. & Watkins, N. D. 1967 Correlation of petrology and natural magnetic polarity in Columbia plateau basalts. *Geophys. J. R. Astr. Soc.* **12**, 405–424.