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Geomagnetic excursions: a critical assessment of the evidence as recorded in sediments of the Brunhes Epoch

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Geomagnetic excursions have tantalized geophysicists since the earliest suggestion of their occurrence over 15 years ago. Either as large-scale geomagnetic secular variation, geomagnetic reversals of short duration or aborted reversals, they held great promise of providing new insights into the nature of the origin of the geomagnetic field. Unfortunately the evidence for geomagnetic excursions from the palaeomagnetic record of Brunhes age sediments is not as compelling as the theoretical arguments. A critical assessment of the available data indicates that the Gothenburg excursion is unlikely to have occurred and the Erieau excursion is very unlikely. The Mono Lake excursion probably occurred, but its absence in nearby contemporaneous sites creates profound problems. The Blake Event appears to be an actual short reversal of complex character, but confirmation of its global nature may be quite difficult.

Introduction

Geomagnetic secular variation and geomagnetic reversals represent two well-documented modes of behaviour of the Earth's magnetic field. Secular variation arises from turbulence in the fluid motions within the Earth's core and hence can be viewed as reflecting the 'normal' state of disorder within the core. Because turbulence is subject to random fluctuations, any measure of the amplitude of secular variation through time will conform to a continuous statistical distribution. The extreme values of this distribution will represent large-scale fluctuations in inclination and declination that may affect only a limited area of the Earth's surface.

Geomagnetic reversals, on the other hand, arise from a wholesale re-organization of fluid motions and hence reflect large-scale re-ordering of the core. The durations of polarity intervals through time have been shown to conform to a continuous probability distribution, at least to first order (Cox 1968; Phillips 1977). This result implies that the reversals are a stochastic process and that geomagnetic reversals of relatively short duration can occur. Detailed analysis of the statistical distribution of the lengths of reversals provides additional evidence that short, undetected reversals have occurred (Harrison 1969; Blakeley & Cox 1972; Aldridge & Jacobs 1974; Tacier *et al.* 1975).

Furthermore, because the reversal process is a stochastic one, there is no reason to expect that every large-scale re-ordering of the fluid motions in the core will lead to a polarity reversal. Unless there exists some triggering mechanism that causes the field to move inexorably from one polarity state to the other, the number of unsuccessful reversals should be at least comparable with if not greater than the number of successful reversals (Cox 1975; Harrison 1980). Like large-scale secular variation, these unsuccessful or aborted reversals would produce large fluctuations in inclination and declination (Hoffman 1981). The fluctuations related to aborted reversals might be of either global or limited regional extent.

Thus there are strong theoretical reasons to expect the occurrence of large-scale geomagnetic secular variation, geomagnetic reversals of short duration, and aborted reversals in the palaeomagnetic record. During an interval of predominantly constant polarity, the signature of each of these features would be magnetic directions whose virtual geomagnetic pole (v.g.p.) deviated substantially from the axial dipole value for that interval. Because the geomagnetic field behaviour responsible for a sequence of anomalous directions may not be immediately apparent, any deviation from the v.g.p. by more than 40° from the axial dipole has been classified as a geomagnetic excursion (Barbetti & McElhinny 1976).

Bonhommet & Babkine (1967) were the first to propose formally that a geomagnetic excursion had occurred during the present Brunhes normal polarity epoch, based on their discovery of reversed inclinations in lavas near Laschamps, France. Since the initial description of the Laschamps excursion, as it is now known, numerous sequences containing anomalous palaeomagnetic directions have been proposed as candidates for geomagnetic excursions. In this paper I shall review the current evidence from the sedimentary record for the occurrence of certain geomagnetic excursions during the Brunhes Epoch. I shall be able to deal only with those excursions that have received the most attention, placing particular emphasis on papers published since the review of Verosub & Banerjee (1977).

Clearly, geomagnetic excursions can be very important to our understanding of geomagnetic secular variation and geomagnetic reversals. However, the problems associated with the palaeomagnetic evidence for geomagnetic excursions must be understood before geomagnetic excursions can provide useful information about the Earth's core. In particular it is important to determine whether during the Brunhes Epoch we are dealing with a few global excursions, with a greater number of non-global excursions, or with no excursions at all. In order to obtain the most meaningful analysis of the data, the limitations of the data must be fully appreciated.

Palaeomagnetic considerations

In dealing with any proposed geomagnetic excursion, the first question is whether the sequence of anomalous directions does in fact represent behaviour of the geomagnetic field. Experience in this area indicates that any proposed geomagnetic excursion should initially be viewed with scepticism. Particularly difficult to verify are proposed geomagnetic excursions from cores of lacustrine and marine sediments. The main problem with such cores is that they are typically of small diameter (10–15 cm) so that it is difficult, if not impossible, to examine in detail sedimentary structures in the vicinity of the anomalous magnetic directions. Such information is important because deformed or disturbed sediments can contain anomalous directions that do not represent behaviour of the magnetic field (Verosub 1975). One situation that deserves particular caution is the occurrence of an anomalous magnetic direction near a distinct change in sediment type. The very fact that there is a lithological boundary implies a drastic change in environmental conditions. The transition from one depositional régime to another may well be accompanied by unstable conditions that may persist even after deposition of a sediment above the lithological boundary.

Even the presence of apparently uniform sediments within a core does not guarantee that the sediments are undisturbed. In the past few years some authors have used the magnetic fabric as determined by the anisotropy of magnetic susceptibility as a means of detecting disturbances in a sediment. In one study Marino & Ellwood (1978) showed that samples from a core from Imuruk Lake, Alaska, had a disturbed magnetic fabric over the same interval in which anomalously low inclinations were measured. Samples from other parts of the core, where the inclinations were not anomalous, had the magnetic fabric characteristic of an undisturbed sediment. In another study Løvlie & Holtedahl (1980) used the change in magnetic fabric to infer that the differences in magnetic directions arose from sedimentological processes rather than from geomagnetic field behaviour.

Other possible causes of anomalous magnetic directions, such as layers of magnetically unstable material, liquefaction-related deformation and problems arising from the coring process, have been discussed by Verosub & Banerjee (1977). Recently Symons *et al.* (1980) showed that shock associated with certain methods of sampling sediments could produce thixotropic behaviour that might result in spurious anomalous directions.

The dating of geomagnetic excursions on the basis of glacial stratigraphy rather than radiometric dating or biostratigraphic correlation can also cause problems. An interval of reversed polarity, first reported by Othberg (1973) from a site in Auburn, Washington, was considered to be of unquestionably late Brunhes age because the sediments contained a tephra horizon that was also contained in the type locality for the early Wisconsinan glaciations in the Puget Sound area. Now the tephra horizon at both sites has been shown to have a zircon fission track age of 0.85 Ma, placing the reversed interval in the Matuyama Epoch (Easterbrook *et al.* 1981).

The preceding discussion illustrates some of the problems involved in trying to establish the existence of a geomagnetic excursion from a single locality. Many of these problems would disappear if the proposed excursion could be found with the same magnetic signature at several sites in different, nearby sedimentary environments. In the past 5 years, considerable effort has been devoted to this approach, unfortunately without definitively positive results. The justification for studies of this type is that a geomagnetic excursion, arising as it does from motions within the core, must affect the surface of the Earth over a finite areal extent. Estimates of the minimal area which must be involved range from 3 to 9 % (Harrison & Ramirez 1975; Denham 1976). These figures correspond to 1500 km as the smallest lateral distance over which a fluctuation in magnetic direction would be observed. Sites within a few hundred kilometres of those with proposed geomagnetic excursions should certainly contain a record of the excursion very similar to that at the original site.

Gothenburg excursion

One excursion for which a search has been made is the Gothenburg excursion proposed by Mörner *et al.* (1971). The original evidence for this excursion is the existence of reversed inclinations in a core from Gothenburg, Sweden. Mörner & Lanser (1974) have suggested that the entire reversed interval lasted from 12400 years B.P. to 12350 years B.P. Aside from possible problems of core dynamics arising from a reversal of such short duration, the validity of the palaeomagnetic record from the core has been questioned on the basis of the consistently scattered values of the declination and the presence of diagenetic magnetic minerals indicating the existence of a chemical remanent magnetization (Verosub & Banerjee 1977). Mörner (1977) has claimed that the excursion is also present at the same stratigraphic level in four other Swedish cores. However, in each of these cases the excursion is represented by a single sample with reversed inclination. The declination values of these samples are not consistent, and it is not clear whether the identification of stratigraphic units is independent of the magnetic results. Thompson & Berglund (1976) conducted a detailed palaeomagnetic study of a core from a site

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located 150 km from Gothenburg. Over the 4.5 m segment spanning the interval 11000 years B.P. to 13000 years B.P. they found no evidence for unusual magnetic behaviour of any kind and concluded that 'using geomagnetic events in the Swedish late Weichselian, is of doubtful value'. In spite of this admonition, erratic directions in post-glacial sediment are often correlated to the Gothenburg excursion, particularly by Quaternary geologists in Europe.

Erieau excursion

Another geomagnetic excursion approximately contemporaneous with the Gothenburg excursion is the Erieau excursion proposed by Creer *et al.* (1976*a*) on the basis of reversed inclinations in two cores from Lake Erie. The reversed interval encompasses glacial till overlain by glacio-lacustrine clay. On the basis of stratigraphic evidence and the correlation of magnetic features, the age of the excursion was estimated as extending from 14000 years B.P. to somewhere between 10500 years B.P. and 7600 years B.P. Several other studies of cores from other Great Lakes probably sampled sediments in this age range but did not find any reversed intervals (Vitorello & Van der Voo 1977; Creer *et al.* 1976*b*; Dodson *et al.* 1977). The most definitive coverage of this time interval is the study of Banerjee *et al.* (1979) which reported on overlapping sections from two postglacial lakes in Minnesota. Sediments from the first lake, Lake St Croix, spanned the interval 0 to 9600 years B.P. while those from the second, Kylen Lake, spanned the interval 9000 years B.P. to 16000 years B.P. No evidence of reversed directions was found at either site. Since the distance from Lake Erie to the Minnesota lakes is only about 900 km, the results of Banerjee *et al.* (1979) provide strong evidence against the existence of the Erieau excursion.

The results from the Minnesota lakes also have a bearing on the Gothenburg excursion. Mörner & Lanser (1974) have claimed that evidence for the global nature of their excursion can be found in results from eastern Canada, the North Atlantic, Mexico and New Zealand. The results of Banerjee *et al.* (1979) do not confirm the Canadian results. Furthermore, the North Atlantic data have been questioned on the basis of the poor preservation of the core from which it was obtained (Opdyke 1976); the results from Mexico are not reproducible even at the original sampling site (Liddicoat *et al.* 1979); and the New Zealand data have been shown to be indistinguishable from a random distribution of directions (Sukroo *et al.* 1978). In view of all of these problems, I do not feel that the existence of either the Gothenburg excursion or the Erieau excursion has yet been confirmed.

Mono Lake excursion

The Mono Lake excursion represents a far more difficult situation than the Gothenburg or Erieau excursions. The excursion was first reported as a eastward swing in declination and a steepening in inclination at two sites exposed in outcrop on the shores of Mono Lake, California (Denham & Cox 1971; Denham 1974). Subsequent work has shown that this behaviour was preceded by a westward swing in declination and a shallowing in inclination (Liddicoat & Coe 1979). The age of the excursion is believed to be about 25000 years B.P. with a duration of 1000 years. The excursion has been modelled as anomalous behaviour of the non-dipole field arising from a small eccentric radial dipole (Denham 1974; Liddicoat & Coe 1979). In this respect the Mono Lake excursion would be classified as large-scale secular variation rather than a phenomenon related to geomagnetic reversals.

As noted above, the excursion occurs in sediments that are sampled in outcrop. The sediments themselves contain very fine, horizontal laminations so there is no possibility that any sedimentary deformation has occurred. Furthermore the excursion has been studied at four separate sites within 100 m of each other, and at all sites the palaeomagnetic signature of the excursion is the same (Liddicoat & Coe 1979). Thus it is very difficult to challenge the reality of the Mono Lake excursion on the basis of sedimentological or palaeomagnetic processes.

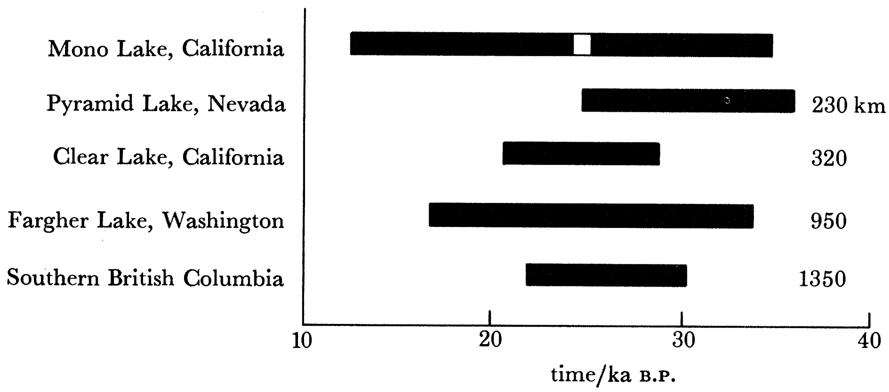

FIGURE 1. Palaeomagnetic evidence related to the Mono Lake excursion. Solid areas represent dated sediments that do not contain anomalous directions, open area represents Mono Lake excursion. On the right are the distances from Mono Lake to each site. Sources of the data are Denham & Cox (1971), Liddicoat & Coe (1979) (Mono Lake), Verosub *et al.* (1980) (Pyramid Lake), Verosub (1977) (Clear Lake), Doh & Steele (1981) (Fargher Lake) and Oberg & Evans (1977) (Southern British Columbia).

The major problem with the Mono Lake excursion, as shown in figure 1, is that studies of contemporaneous lake sediments have failed to confirm its existence (Verosub 1977; Oberg & Evans 1977; Verosub *et al.* 1980; Doh & Steele 1981). In particular any magnetic field behaviour arising from fluid motions in the core and 'seen' at Mono Lake must certainly have been 'seen' at Pyramid Lake and at Clear Lake which are, respectively, only 230 and 320 km from Mono Lake. This situation has led to doubts about the dating of the Mono Lake excursion (Verosub *et al.* 1980) because the dating was originally based on extrapolation from two younger radiocarbon dates (Denham & Cox 1971). Recently 16 new radiocarbon dates from above and below the excursion have confirmed the original dating (K. R. LaJoie, personal communication 1981).

These new results create a major dilemma, for it appears that the 1000 year sedimentary record representing the Mono Lake excursion is present in only one lacustrine sequence out of five. Even if we focus on the 200 year interval during which the directions are most anomalous we are still forced to conclude that gaps of several hundred years duration must be common in all lacustrine sequences. Although lacustrine sedimentation is expected to be neither uniform nor continuous, the frequent occurrence of gaps of this length is totally unexpected and inconsistent with the results from those lacustrine sequences for which many radiocarbon dates are available. In fact if this conclusion about sedimentation in lacustrine environments were true, almost all studies of secular variation of lacustrine sediments would be meaningless. The alternative is to assume that the Mono Lake excursion occurred during an interval of very rapid sedimentation, so that its actual duration is perhaps 100 years rather than 1000 years.

In this case the critical missing interval would represent only 20 years, and it is not unreasonable that it was missed by the other studies.

This solution leaves a question that the core dynamicists must answer: What is the upper limit to the rate at which large changes in magnetic directions at the surface of the Earth can occur in response to fluid motions in the core? If the limit is high enough, it might explain the Mono Lake dilemma as well as resolve some of the difficulties associated with the Gothenburg excursion.

Blake Event

The last excursion with which I shall deal is the Blake Event, first proposed by Smith & Foster (1969) on the basis of the occurrence of reversed samples in the same foraminiferal zone of several deep-sea cores. The estimated age of the excursion was 111000 years with a duration of 6000 years. Recently, reversed intervals of about the same age have been reported in three cores from the western North Atlantic (Denham 1976; Denham *et al.* 1977), in a marine terrace section in Japan (Manabe 1977) and in a core from Italy (Creer *et al.* 1980).

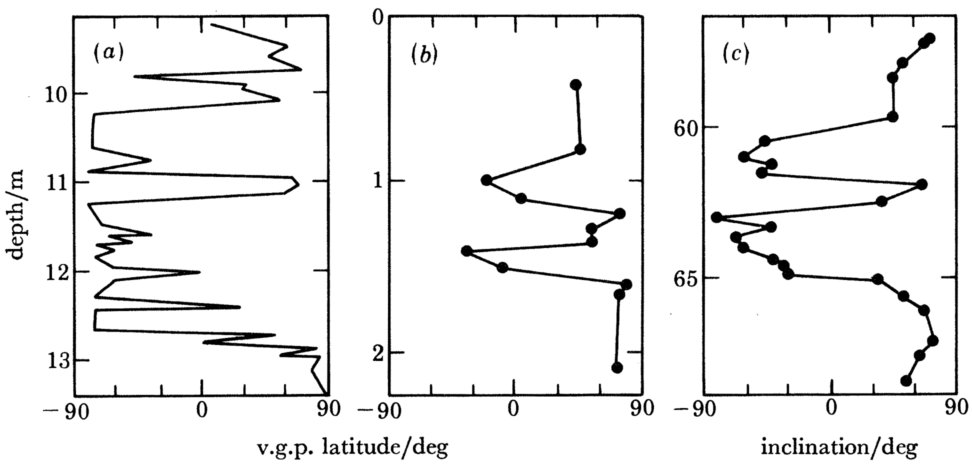

Figure 2. Palaeomagnetic records believed to represent the Blake Event: (*a*) North Atlantic; (*b*) Japan; (*c*) Italy. Each record has been arbitrarily stretched to produce the same apparent duration. Only inclination values are available for the Italian data. Sources of the data are Denham (1976) (Atlantic Ocean), Manabe (1977) (Japan), and Creer *et al.* (1980) (Italy).

Aside from the general questions that can be raised regarding the occurrence of an excursion in any sediment core, the sediments presumably containing the Blake Event each have their own particular problems. Not all of the magnetic directions of the original cores of Smith & Foster (1969) are unambiguously reversed (Denham 1976); the three cores from the western North Atlantic contain many additional older reversed intervals in the Brunhes which are not seen in other cores (Denham 1976; Denham *et al.* 1977); the dating of the Blake Event in the Japanese record is based primarily on palaeoclimatological rather than palaeontological evidence; and the dating of the Blake Event in the Italian core is based on extrapolation from the biostratigraphic identification of the Plio-Pleistocene boundary, which is itself not unambiguously located. In spite of these problems the palaeomagnetic records for the Blake Event, particularly those from the Japanese section, the Italian core and the three western Atlantic cores are considerably more convincing than those of either the Gothenburg or Erieau excursions because the magnetic directions are fully reversed over a significant sampling interval. Whether all of the Blake Event records actually represent the same excursion is a difficult problem because the 100000 to 125000 year age range is extremely difficult to date precisely either radiochemically or palaeontologically. Thus it is unlikely that the time resolution needed to establish synchronicity will ever be attained. The best hope in this respect resides with the palaeomagnetic signal itself. In the Italian record, the Japanese record and at least two of the western North Atlantic records the Blake Event appears as two reversed intervals separated by a short normal interval (figure 2). If this feature can be found at other sites in sediments of approximately the correct age, the relatively convincing case for the Blake Event will be considerably strengthened.

Conclusion

The search for geomagnetic excursions in the palaeomagnetic record of Brunhes age sediments has been a difficult and frustrating one. Fifteen years after the existence of the first geomagnetic excursion was formally proposed, the sedimentary record has not yet yielded incontrovertible evidence for the occurrence of a single geomagnetic excursion. Each of the four excursions most prominently mentioned still has problems associated with it. Based on the available evidence I conclude that it is unlikely that the Gothenburg excursion actually occurred unless it was of very short duration, a circumstance probably in conflict with core dynamics. It is very unlikely that the Erieau excursion occurred. The Mono Lake excursion probably occurred but its absence in nearby, contemporaneous sites raises profound palaeomagnetic and sedimentological problems. Strong evidence exists for one or more excursions at the time of the proposed Blake Event. The Blake Event is very probably an actual short reversal of complex character; however, it may be quite difficult to confirm its global character.

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