PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A
MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

Transition fields during geomagnetic reversals and their geodynamic significance

Emilio Herrero-Bervera and S. Keith Runcorn

Phil. Trans. R. Soc. Lond. A 1997 **355**, 1713-1742
doi: 10.1098/rsta.1997.0089

Transition fields during geomagnetic reversals and their geodynamic significance

By Emilio Herrero-Bervera[1] and S. Keith Runcorn[2]†

[1] *School of Ocean and Earth Sciences and Technology (SOEST), Hawaii Institute of Geophysics and Planetology (HIGP), Paleomagnetic Laboratory, University of Hawaii, 2525 Correa Rd, Honolulu, HI 96822, USA*

[2] *University of Alaska, Fairbanks, Alaska, USA, and Space and Atmospheric Physics Group, The Blackett Laboratory, Imperial College of Science, Technology and Medicine, London SW7 2BZ, UK*

Contents

The paths of the virtual geomagnetic poles (VGPs), which are north magnetic poles conventionally calculated from the axial dipole formula, describing the transitional fields during Cenozoic polarity reversals, are presented. They provide evidence that, at least on a number of occasions, the transitional field recorded by sediments is predominantly dipolar. The VGP paths are mostly confined to two longitudinal sectors which are 180° apart, the first path passing over the Americas and the second over Australia and East Asia. The mantle 'guides' the rotating dipole along these preferred paths. However, a much smaller number of records show that for certain reversals, a path midway between the two preferred paths (i.e. a path across the Atlantic and the mid-Pacific) is favoured. We regard this as an important key to the mechanism.

Two hypotheses to explain these observations have been put forward. The first hypothesis notes that the preferred paths correlate roughly with two seismic tomography anomalies in the lower mantle that have been interpreted as lateral temperature anomalies associated with mantle convection. It is then suggested that the diffusion of these thermal anomalies somehow controls the core dynamo and its mode of reversal. Others have already suggested that undulations on the core mantle boundary could exert a controlling influence on core motions and therefore the behaviour of the dynamo. The alternate view simply accepts the concept that the dynamo reverses by

† Deceased 5 December 1995.

dipole rotation and that the D'' layer is hemispherically asymmetric chemically: its quasi-metallic conductivity under the Pacific hemisphere had long ago been proposed to explain the low geomagnetic secular variation and non-dipole field observed there. The torques, resulting from the electromagnetic induction in the D'' layer by the reversing dipole rotate the core about the Earth's axis until the VGP path lies along either of the bounding meridians of the shell. The data presented on transitional polar paths should provide a test between the two theories.

1. Introduction

Even though the reversal of polarity of the geomagnetic field is one of the most remarkable of the Earth's phenomena, the processes in the Earth's core that cause it are little understood. An essential step to the understanding of this instability of the core dynamo is the study of the transitional fields that are preserved in palaeomagnetic records. Polarity reversals have been recorded in a wide variety of rocks (deep-sea sediments, continental sedimentary rocks, intrusive and extrusive igneous rocks) in which the physicochemical processes of formation and of magnetization are diverse. As the magnetostratigraphy over the last 160 Ma, dated by radioactive methods, and the less complete one since 600 Ma ago were developed, it was recognized early on that reversals occurred in a very short time period, geologically speaking, perhaps in a few thousand years. It has only been in recent years that the remarkable advance of determining the directions and intensity of the geomagnetic field during some polarity transitions has been made. These records have been mostly from sediments, which average the recorded field over varying time intervals, but in a few cases field directions at intervals during transitions have been obtained from igneous rocks. It was recognized from such records that it would eventually be possible to draw some general conclusions as to how geomagnetic reversals occur and to produce a model of the reversing core dynamo.

The past two decades have seen an increasing number of studies of such reversal transition records. The controversies about their interpretation will be a main concern of this paper. Several transitional field models were developed, and attempts have been made to relate them to the dynamics of the outer core. At one time it was thought that the dipole disappeared during reversals, as it was noticed early on that the remanent magnetization intensity was reduced just before and just after the change in field direction (e.g. Opdyke 1972). Then there was speculation that the transitional fields retained a primarily dipolar character (e.g. Creer & Ispir 1970; Steinhauser & Vincenz 1973; Hammond *et al.* 1979). But when better data were obtained, these investigations took a new direction putting aside both of these simple ideas (e.g. Bogue & Coe 1984; Hoffman 1977; Hoffman & Fuller 1978; Fuller *et al.* 1979; Williams & Fuller 1981; Hoffman 1982; Kaiser & Verosub 1985). Comparing the palaeomagnetic records of the Matuyama–Brunhes reversal (0.783 Ma) from five widely differing sites, Hoffman & Fuller (1978) and Fuller *et al.* (1979) found that the VGP path fell, in each case, near the longitude of the site, showing that the field did not remain dipolar during the reversal process. They concluded that the transitional fields were predominantly higher-order zonal harmonics, axial quadruples octupoles, i.e. that they were axisymmetric but not dipolar. As more detailed records of other reversals were obtained, evidence in conflict with these simple models were found.

Clement (1991) argued that the transitional fields were neither axisymmetrical nor dipolar, i.e. they were non-zonal harmonics of low degree. Such views gained wide acceptance. Obviously the determination of the higher-degree harmonics of transitional geomagnetic fields required a worldwide distribution of records and a very accurate dating of them.

The results reviewed in this paper, along with recent papers of the group at Gif-sur-Yvette in France (Tric *et al.* 1991*a*, *b*) question the conventional wisdom of the last decade that the transitional fields are wholly dominated by non-dipolar components. These results suggest instead that the earlier speculations (by, for example, Creer & Ispir 1970; Steinhauser & Vincenz 1973; Hammond *et al.* 1979) may have been nearer the truth. We argue that the transitional palaeomagnetic fields recorded in many sediments are predominantly dipolar (with minor contributions from non-dipolar fields) and that the VGP paths during many late Cenozoic reversals lie mainly across the Americas and 180° away across Australia and East Asia.

Yet an entirely different conclusion has recently been drawn by Prévot & Camps (1993) from lava flows of the last 10–11 Ma that record polarity transitions. Because the extrusion of lavas is intermittent, the average number of lava flows recording a transitional field is about three or four, but about 100 transitional records, either different in time or from different sites world wide are available. Prévot & Camps showed that the VGPs of these recorded transitional fields were completely scattered over the globe and showed no evidence of preferred paths. Because lavas become magnetized by the process of thermoremanent magnetization (TRM), (well understood both theoretically and experimentally), the field recorded is that of the short time (about 1 yr) in which the lava flow cools from above the Curie point down to ambient temperatures. Prévot & Camps argued that these records were inherently more reliable than those of the sediments. Their conclusion was that the preferred paths were artifacts of the complex processes of sedimentary deposition and magnetization. We nevertheless will conclude with Laj *et al.* (1991, 1992, 1993) that the transitional fields of at least some of the geomagnetic reversals in the late Cenozoic times showed that they occurred essentially by the rotation of the dipole through 180° and mainly along two longitudinal sectors which we term the 'preferred paths' located in the Americas and in Australia–Asia.

2. Summary of the transitional data available

In spite of the considerable effort in sampling and analysing palaeomagnetic sections all over the world that has provided a detailed magnetostratigraphy, i.e. dated horizons of polarity reversals in the geological column, records of transitional fields with sufficient numbers of palaeomagnetic samples to trace each reversal through time remain relatively few. Because such transitional records are available for few reversals and have a restricted geographical coverage and are of varying quality, as we will see, inferences about the reversal process must be somewhat tentative at present. Nevertheless it needs to be remembered that the sampling of this phenomena has, perforce, been random in space and time, for the transitions studied, and the sites from which the VGP paths have been calculated, have not been chosen on any theoretical grounds, but by the complex geological processes of nature that have provided reversal records suitable for detailed sampling. Moreover, since the dynamo in the Earth's core generating the geomagnetic field is not well understood, especially concerning reversals, the experimenter comes to this study without preconceived notions. Obviously, attempts to model the transitional field mathematically must be incomplete. When we say that the transitional geomagnetic field, as recorded by the remanent magnetization of samples, is dipolar, we mean that, as with the geomagnetic field today, non-dipolar components are present to only a small percentage of the total components (about 15% is characteristic of the Earth today). It is found that if the geomagnetic field is smoothed over times as short as 10^2–10^3 yr, it becomes almost wholly dipolar, and it has long been known that the mean fields of either polarity in the last few 10^7 yr are dipoles aligned along the axis of the Earth's rotation (Hospers 1953). Meaningful determinations of the poles can, in consequence, be made using the famous dipole formula to give the palaeolatitude from the angle of magnetic dip or inclination. On the other hand, when we speak of the non-dipolar field, we do not imply that dipolar components are non-existent, but that a meaningful axis cannot be calculated from the observed distribution of palaeofield directions. Divergence between the VGP paths for transitional fields from different sites throughout the world implies that either the transitional field is non-dipolar with perhaps several different harmonics of varying strengths, or that the rocks at different sites have failed to record the transitional dipolar field faithfully. However, a non-dipolar transition field much greater than 15% of the dipole component might consist of a perfectly axial non-dipolar field with a small rotating dipole. Then the VGP longitude would be wholly determined by the dipole. We should also remark that there is no theoretical reason why the configuration (dipolar or non-dipolar) of the reversing geomagnetic field should be the same for different reversals.

The results by the Gif-sur-Yvette group, which reopened the question so effectively, are all from localities in the Mediterranean and are listed in table 1: the Blake event (locality 1), the Upper Olduvai (locality 8), five Early Miocene reversals (locality 15) and three Pliocene reversals (locality 16).

These reversal records showed that the transitional VGPs tended to fall across the Americas or 180° away in longitude near Australia and East Asia, convincingly in (1) and (8) and with two exceptions to be discussed later in (15) but only suggestively in (16). It has been held (Runcorn 1992) that these VGP data alone showed that the field reversed, at least on these occasions, by the rotation of the dipole: for if the transitional field were predominantly non-dipolar, the VGPs calculated from the palaeomagnetic directions would have no physical meaning and their association with only restricted regions of the mantle could not possibly have any geophysical explanation. However, these preferred longitudinal sectors are roughly 90° from the longitudes of these Mediterranean sites, and this curious circumstance naturally raised the question of whether it was somehow an indication of a non-dipolar field configuration, for as we have explained, when it appeared that each VGP path for the 0.783 Ma reversal fell near its site, the transitional field was interpreted as an axial quadrupole or octupole. Could this 90° feature therefore result from a non-axial non-dipolar transitional field? It can, however, be shown that no field of internal origin possesses the above property for sites other than specific ones, so the VGP paths obtained from the sites in the Mediterranean region do really provide strong evidence that the transition fields were dipolar. However, the convincing proof of how reversal takes place, clearly requires contemporaneous records from sites that are well distributed over both hemispheres.

We have therefore chosen for discussion a number of reversals, for which palaeomagnetic records have been obtained from widely separated localities listed in table 1: the Blake and Pringle Falls (figures 1–3), Cobb Mountain (figure 7), Jaramillo

Table 1. *Transitions discussed in this paper*

locality	reversal	age (Ma)	sedimentation rate (cm ka^{-1})	reference
(1) East Mediterranean (32° 14'N, 33° 45'E)	Blake	0.120	5–10	Tric *et al.* 1991*b*
(2) Long Valley, CA	Pringle Falls	0.218	15–85	Liddicoat 1989
(3*a*, *b*) La Pine, OR, USA	Pringle Falls	0.218	15–85	Herrero-Bervera *et al.* 1994
(4) Central Pacific core K78030	Upper Jaramillo	1.07	3.5	Herrero-Bervera *et al.* 1986
(5) Tahiti	Upper Jaramillo	0.992	lavas	Chauvin *et al.* 1990
(6) Central Pacific	Lower Jaramillo	0.99	3.5	Herrero-Bervera 1986
(7) Cobb Mountain DSDP 609B, 647B	Cobb Mountain	1.1	4.5	Clement & Martinson 1992
(8) Crostolo section, Po Valley, Italy	Upper Olduvai	1.77	85	Tric *et al.* 1991*a*
(9*a*, *b*) Indian Ocean RC14-14	Upper Olduvai	1.77	1.7–6.7	Clement & Kent 1985
(10) North Central Pacific core K7501	Upper Olduvai	1.77	1.63	Herrero-Bervera & Khan 1992
(11) North Central Pacific core K78019	Upper Olduvai	1.77	1.7	Herrero-Bervera & Theyer 1986
(12) Central Pacific core K78019	Lower Olduvai	1.95	3.52	Herrero-Bervera *et al.* 1987
(13) Central Pacific core K76113	Lower Olduvai	1.95	1.1	Herrero-Bervera *et al.* 1987
(14) Mar. Del Plata Argentina	Gauss–Matuyama	2.6	1.0	Ruocco 1991
(15) Crete	5 Miocene reversals	5.5–7.8	4.0	Valet *et al.* 1988
(16) Zachintos	3 Pliocene reversals	10–11 Ma	2–3	Laj *et al.* 1988

(figures 4–6), Olduvai (figures 8–12) and Gauss–Matuyama (figure 14) reversals†. The choice of records inevitably involves somewhat subjective judgments as to what constitutes a minimum number of samples to delineate the reversing field in sufficient detail, but we believe the records chosen do this and together they clarify the

† General information about legends. Each solid black dot is a VGP calculated from one sample and lines connect samples adjacent stratigraphically. Full lines are likely to be realistic paths while dashed lines are not regarded as such but only indicate adjacent samples. Dots encircled by dashed circles are regarded as being of low reliability. The sampling sites are shown by stars.

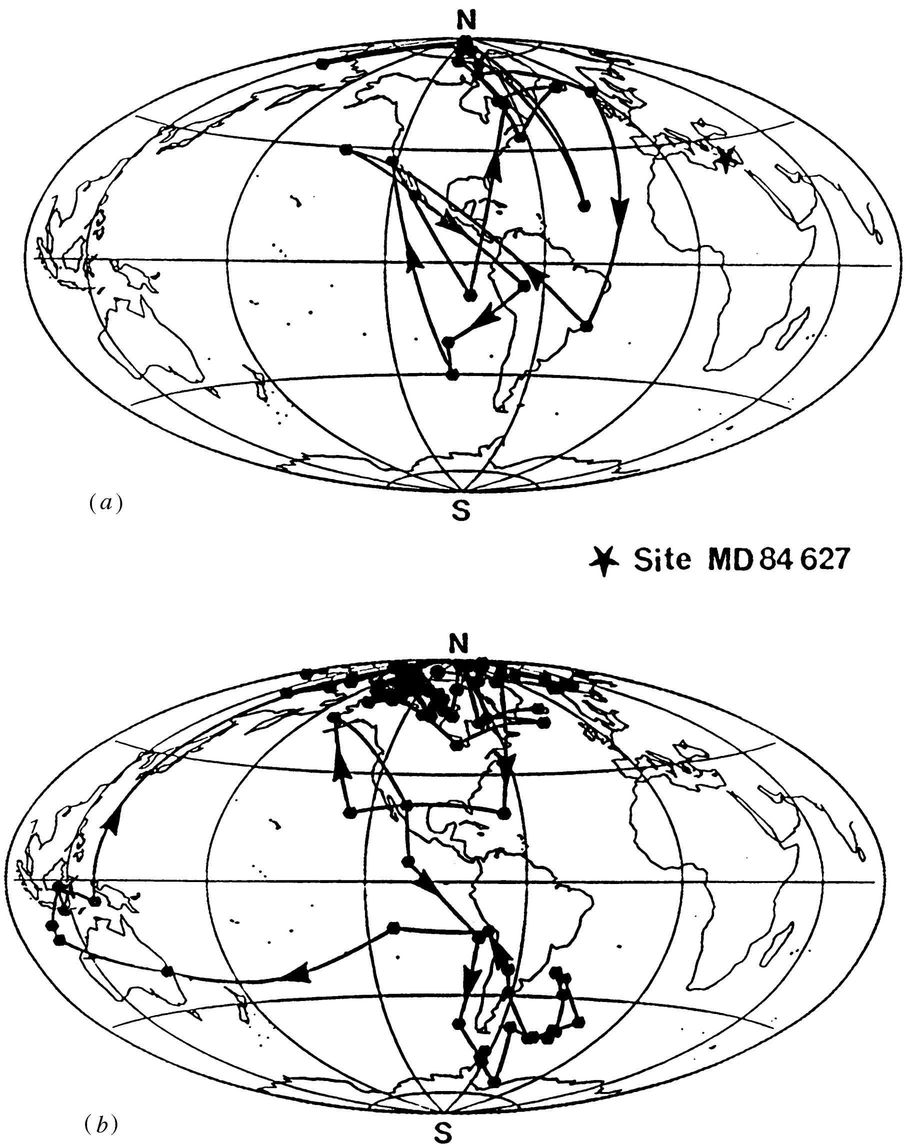


Figure 1. VGP path of the Blake geomagnetic polarity episode. East Mediterranean oceanic core (Tric *et al.* 1991*b*).

basic behaviour of the field. But the alternative approach of lumping together all transitional records in the literature has been tried by McFadden *et al.* (1993). A similar conclusion is reached to that of this paper, i.e. that preferred paths are a real phenomenon of the reversing dynamo in the late Cenozoic.

3. The reliability of the palaeomagnetic records of transitions

The reliability of the deep-sea sediment cores for palaeomagnetic analysis has been critically studied, for example, by Clement & Kent (1985, 1987). The high degree of internal consistency of the data and the general magnetic stability of these sed-

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

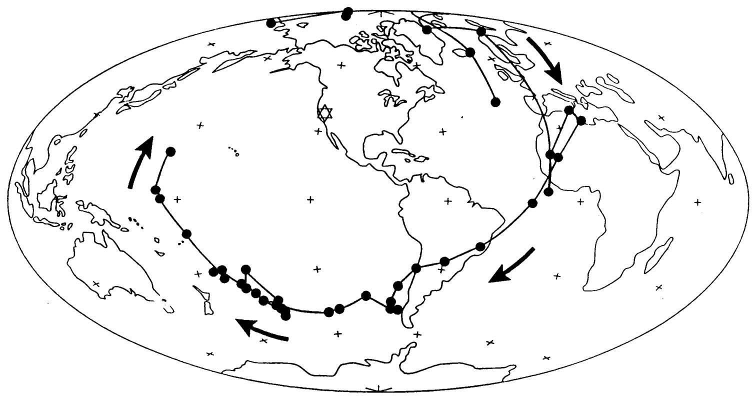
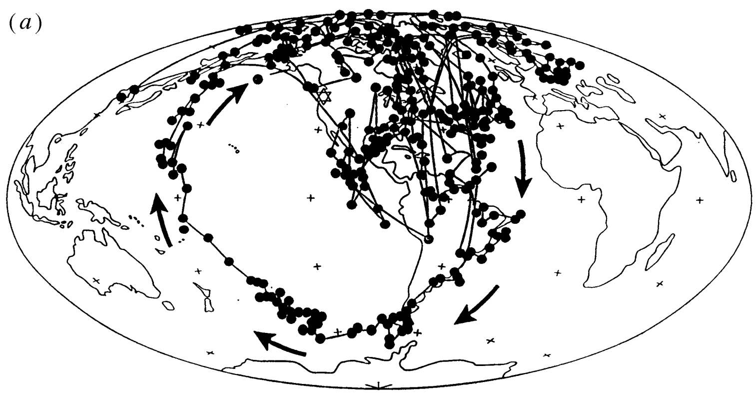


Figure 2. VGP path of the Pringle Falls polarity episode at Long Valley Site A (Liddicoat 1990).

(*a*)



(*b*)

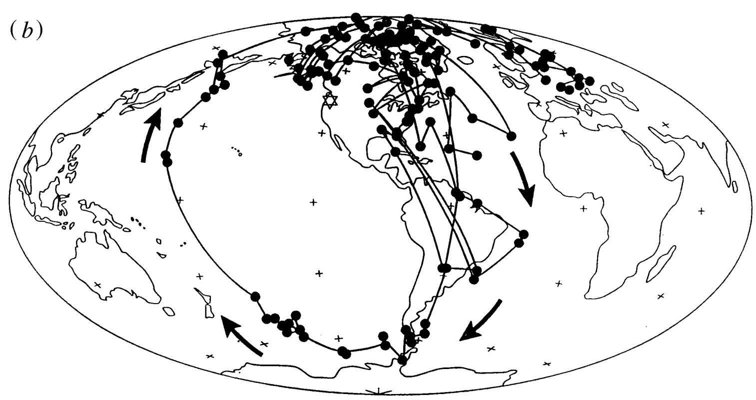


Figure 3. VGP paths of the Pringle Falls polarity episode at Pringle Falls, Oregon USA (Herrero-Bervera *et al.* 1989, 1994; Herrero-Bervera & Helsley 1993).

iments as a rule has been widely recognized. The geomagnetic field at the time of deposition or compaction is normally recorded by the primary field directions that remain after the samples are demagnetized by alternating fields of the order of 10 mT, which remove the secondary magnetizations, i.e. the low coercivity overprints picked up—perhaps in the laboratory treatment or in the coring process. Other laboratory

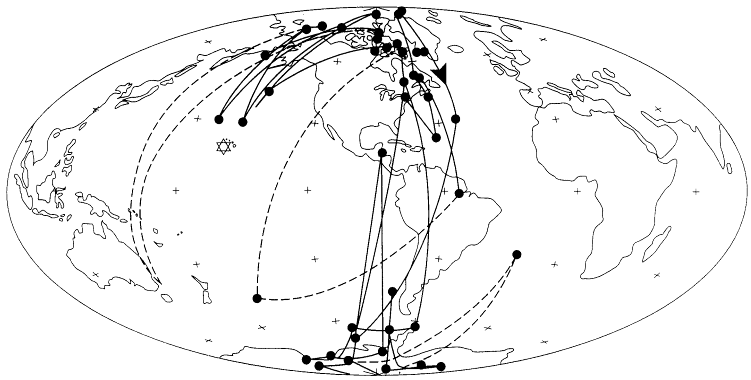


Figure 4. VGP paths of the Jaramillo reversals: Upper Jaramillo from Central Pacific Core K78030 (Herrero-Bervera & Theyer (986).

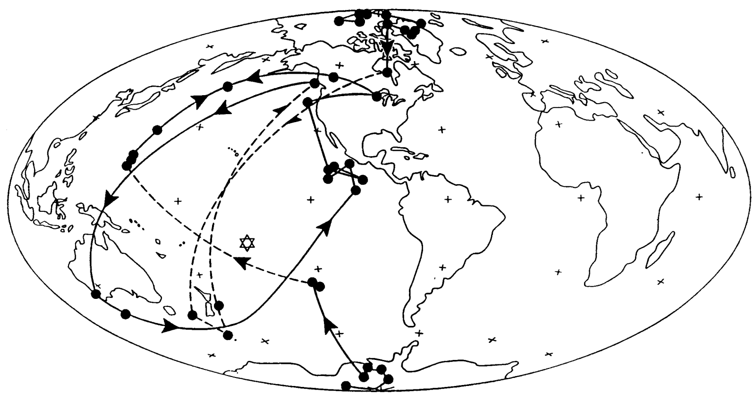


Figure 5. VGP paths in geographical coordinates of the Jaramillo reversals: Upper Jaramillo reversal recorded in Tahiti (Chauvin *et al.* 1990).

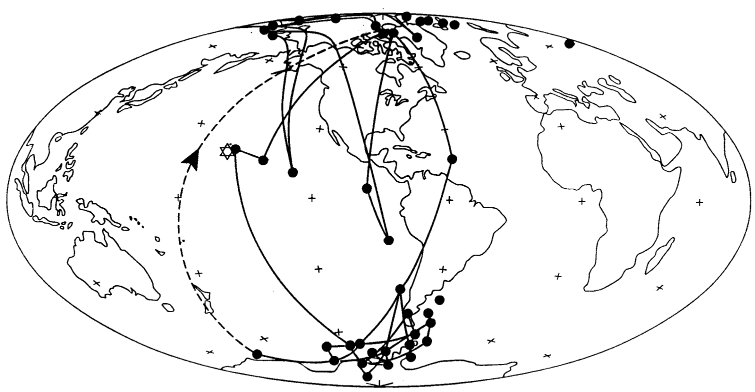


Figure 6. Lower Jaramillo reversal recorded in Central Pacific core K78030 (Herrero-Bervera & Theyer 1986).

experiments have been done, such as giving the samples an anhysteretic remanent magnetization (ARM) in which a rock or a laboratory-prepared specimen is subjected to an alternating field, as in the demagnetization process, but with a small steady field superimposed: the specimen acquires a remanent magnetization proportional to

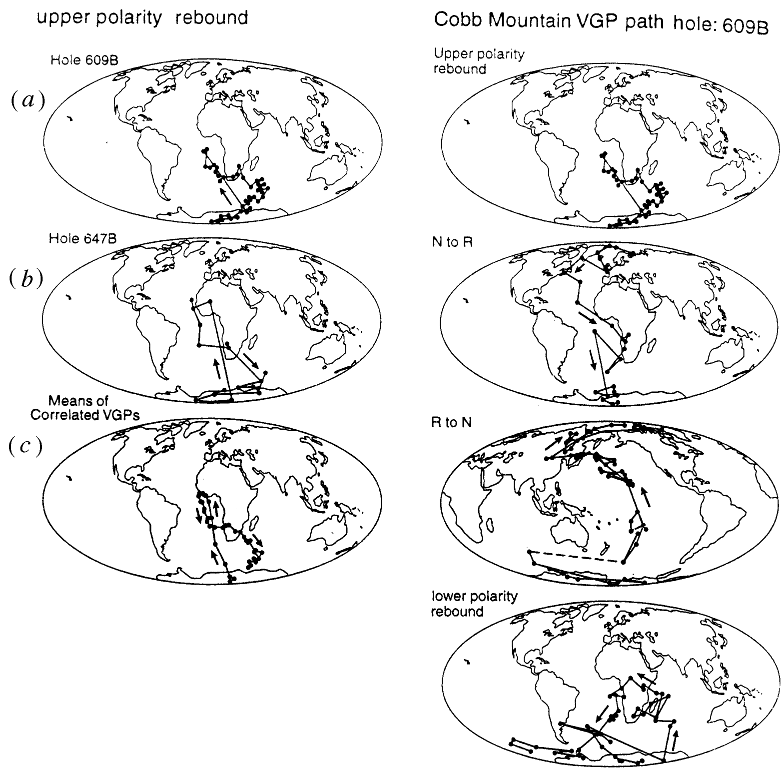


Figure 7. VGP paths in geographical coordinates of the Cobb Mountain fom DSDP Hole 609B, 647B (Clement & Martinson 1992).

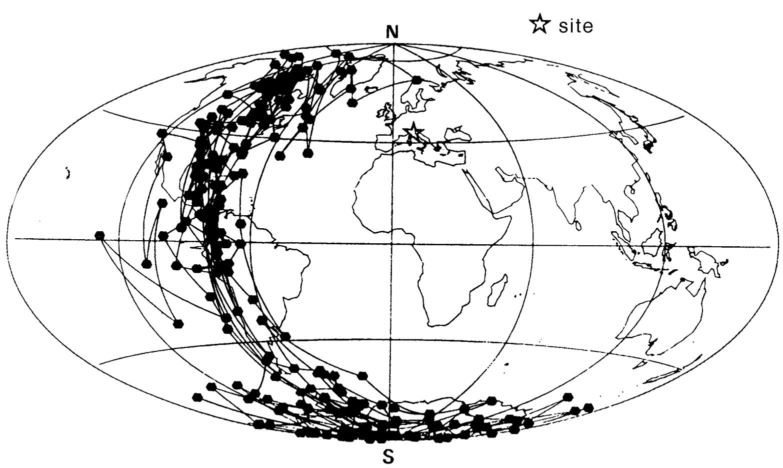


Figure 8. Upper Olduvai reversal record from Crostolo, Po Valley (Tric *et al.* 1991*a*).

the steady field. This magnetization intensity, if divided into the natural intensity of magnetization (NRM), normalizes the latter, monitoring the magnetization process in the section sampled, and is a measure of the palaeointensity of the geomagnetic field. This procedure gives reliable relative values of the Earth's field before, during and after reversal, even though its absolute value is very difficult to obtain from sedi-

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

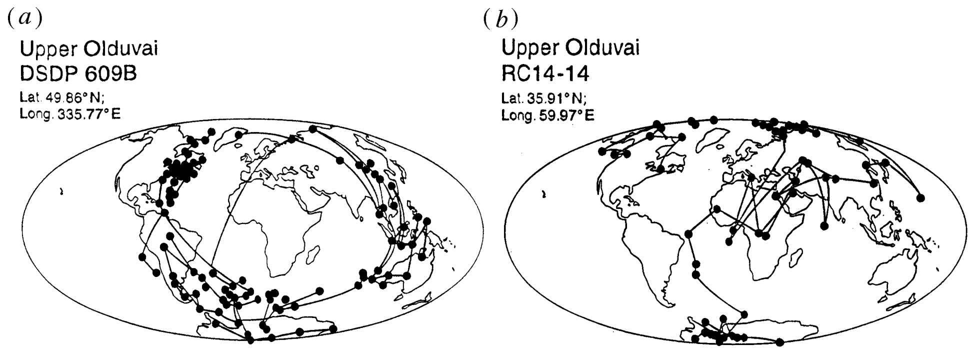


Figure 9. (*a*) VGP path of the Termination (Upper) Olduvai. North Atlantic DSDP site 609B (Clement & Kent 1987). (*b*) VGP path of the Upper Olduvai reversal from the South Indian Ocean core RC14-14 (Clement & Kent 1985).

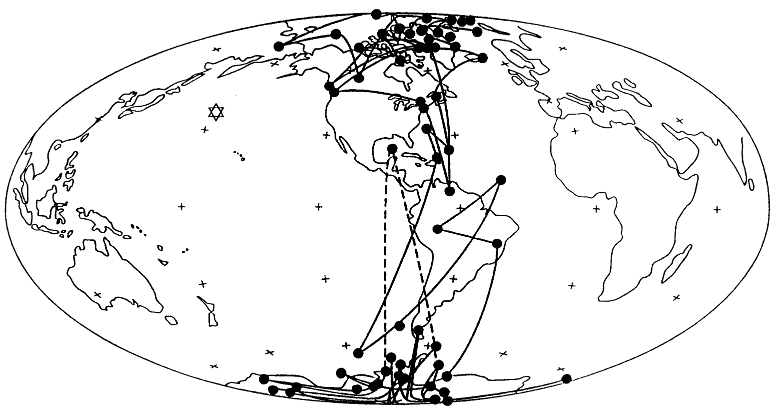


Figure 10. VGP path of the Upper Olduvai reversal from the Central Pacific Core K7501 (Herrero-Bervera & Khan 1992).

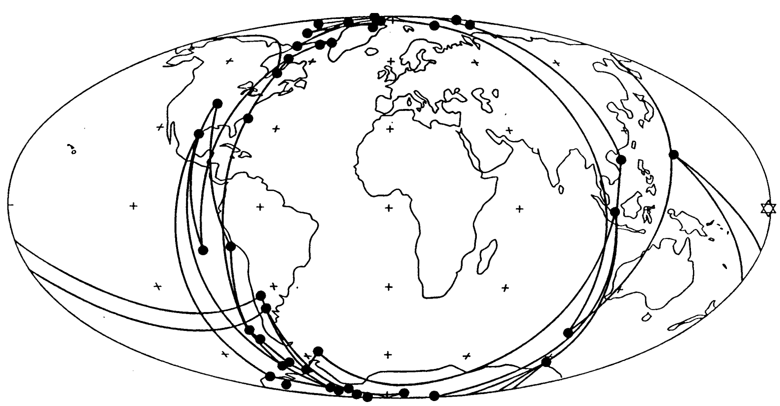


Figure 11. VGP path of the Lower Olduvai reversal from the Central Pacific Core K78019 (Herrero-Bervera *et al.* 1987).

ments. The Olduvai Subchron is dated at 1.77–1.95 Ma (Shackleton *et al.* 1990). The Jaramillo reversal samples dated at 0.99–1.07 Ma (Shackleton *et al.* 1990). The Blake geomagnetic polarity episode is observed in a core from the eastern Mediterranean, and is dated at 0.120–0.150 Ma, but at Pringle Falls, OR, as 0.218 Ma.

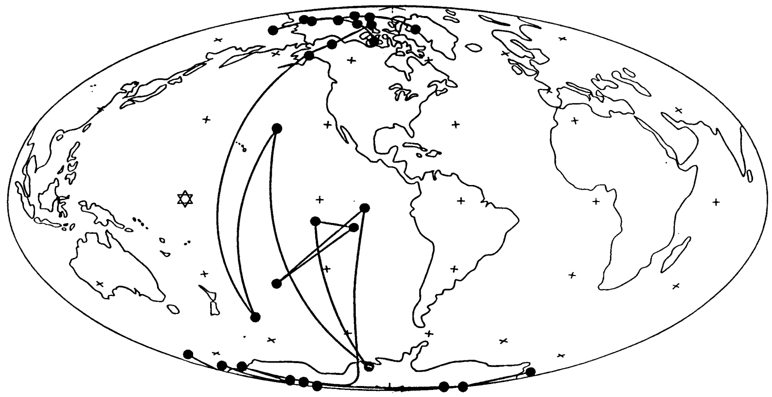


Figure 12. VGP path of the Lower Olduvai reversal form the Central Pacific Core K76113 (Herrero-Bervera *et al.* 1987).

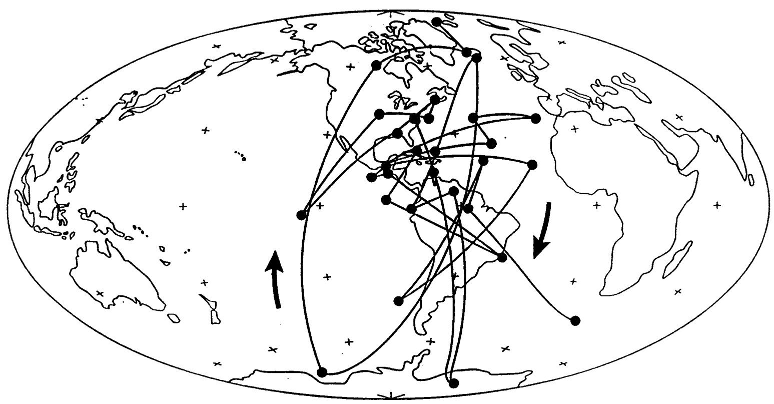


Figure 13. VGP paths of the Gauss–Matuyama reversal boundary from Mar del Plata, Argentina (Ruocco 1991).

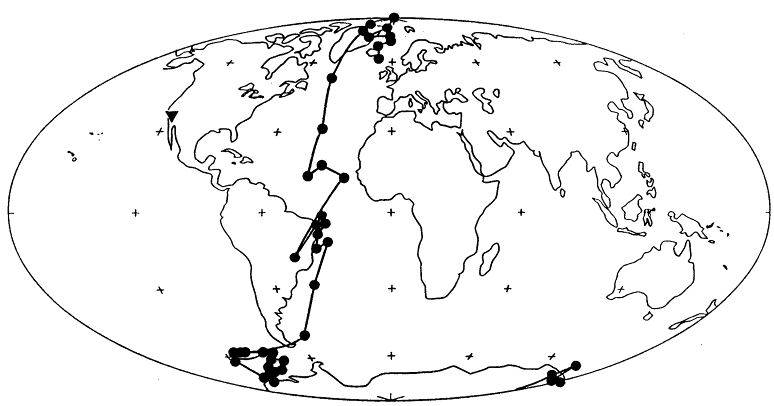


Figure 14. VGP path of the Gauss–Matuyama reversal boundary from Searles Valley, California (Liddicoat 1982).

There are similarities in all these transitional records obtained in different laboratories and from the many different sampling sites, which point to a global rather than to a local magnetization process. This seems to make it implausible to explain away the main features of these records, i.e. confinement of the VGPs to longitudinal sectors, as artifacts arising from multicomponent magnetization processes. Nevertheless such explanations, postulating the superposition of components acquired from the changing geomagnetic fields at different times, or from magnetizations distorted or dominated by currents or biological activity during the deposition process have been put forward, and they need to be rigorously tested against the observational data. There are records in which these VGP preferred paths are not evident, and these must be examined to determine whether these sediments have truly preserved the ambient fields or whether they cast doubt on all sedimentary records. David Schram, the distinguished American astronomer, in a current cosmological controversy has remarked that 'whenever you are at the forefront of science, one third of the observational results always turns out to be wrong'. Laboratory experiments, involving redepositing sedimentary material in varying environmental conditions to study the acquisition of remanent magnetization from the ambient fields, can neither prove that any particular geological sedimentary deposit did faithfully record the varying geomagnetic field nor that processes such as 'inclination error' were important. We cannot reproduce in the laboratory the sedimentation rates and later diagenetic changes or the natural environment of the deep oceans. However, the slow deposition of sediments does mean that, quite apart from any physical processes which may cause divergences between the ambient field and the remanent magnetization directions, some form of mean field, rather than, in the case of lava flows, 'instantaneous fields', will inevitably be recorded.

Oddly enough an important insight into sedimentary magnetization is given by the recent investigation of the VGPs in lavas from transitional zones, to which we have already referred, by Prévot & Camps (1993). They argued that the sedimentary magnetic record is unreliable, and in particular that the confinement of the VGPs in two longitude sectors is not a property of the geomagnetic field but an artifact of the possible processes just referred to. Prévot & Camps (1993) examined about 400 palaeomagnetic directions of lavas for which they judge that there is evidence of stability. They calculated VGPs for each, and by statistical tests showed that the VGPs are randomly scattered over the globe. These are from 121 reversal records from worldwide sites. Thus on average, each transition is delineated by only 3–4 spot field directions. For lavas acquire remanent magnetization by the TRM process in a few months or a year, and if secondary magnetizations are present, it is usually viscous remanent magnetization acquired from the present geomagnetic field, which has routinely been removed by a.c. demagnetization. Because of the random scatter of the VGPs, they conclude that the sedimentary records of transitions are 'unrealiable', that the field is 'statistically axisymmetrical during polarity reversals' and that there is 'no palaeomagnetic evidence for a control of reversal morphology by the lowest region of the mantle'. But they do not refer to the evidence that during transition the palaeointensities are lower by a factor of 2–5 from the sediments (Tauxe 1993). This is collaborated by the absolute palaeointensities of transition fields determined by the Thellier–Thellier method from lavas from the islands of Kauai and Oahu, Hawaii; and also from Steens Mountain, Oregon (e.g. Bogue & Coe 1984; Prévot *et al.* 1985). Since the relative strength of the non-dipole field is about 15% of the dipole component during stable polarities in the late Cenozoic as it has been in prehistoric times, it means that the dipole moment diminishes by a factor of 2–5. Therefore if the non-dipolar field remains in the same order during transitions, then the scatter of spot readings of the field directions, such as those that the lavas provide, will be increased by 2–5 times and the VGPs calculated from each lava will have no physical meaning. The lava record, as analysed by Prévot & Camps, therefore, does not justify their three conclusions discussed above. In fact the VGP in such cases is not a pole that has a physical meaning, as Runcorn (1996) explains, and therefore their maps showing the distribution of VGPs are very misleading in our present discussions.

The only rational interpretation, of the discrepancy between the sedimentary VGP preferred paths and Prévot & Camps' maps of VGPs scattered 'randomly' over the globe, is the opposite of their conclusion. What their work really demonstrates is that sedimentary records smooth out much of the non-dipole components (in historic times the secular variation has strong periods of between 100 and 1000 yr) thus revealing the behaviour of the dipole during transition between the polarities, which is obviously the main aim in studying the reversal process. The insight which this interpretation of Prévot & Camp's paper affords us is crucial to the understanding of sedimentary records. The smoothing times of the field recording process in different sedimentary records or even within one section may be expected to differ. Therefore anomalous VGPs during transitions, when the VGP paths are otherwise smooth, or entirely anomalous transition records when the VGPs are greatly scattered, may be correctly preserving the ambient field direction but not averaging out the non-dipole field to reveal the dipole behaviour. It is what happens to the dipole during reversal that is fundamental to the understanding of the core dynamo reversal and the mechanism by which the mantle guides it. Consequently, as seen in this paper, the VGPs in one section, e.g. in the Po valley (figure 8), very clearly follow a 'preferred' path while in other cases the VGPs only roughly delineate a preferred path. Evidently some non-dipole components remain that cause divergence from the dipole path to different extents in different records. Exploring further the nature of the preferred paths derived from sedimentary records, one can say that in effect, the lava data may be right but do not give us what we want (i.e. information on the dipole)! Therefore it can be suggested that if the lava data are right then they are telling us exactly what we want to know, namely, that the field is not predominantly dipolar during reversal (as mentioned earlier, but a combination of dipolar plus non-dipolar components). Then, the aim is to understand the geomagnetic field without the all-too-prevalent bias toward giving the dipole excessive prominence in that study. If it is really true that the sediments are less susceptible to the non-dipole effects (a debatable assertion since it is based on an argument by an unsound analogy between the current field and reversals fields), then the point is well made that the sediments may tell us something useful in terms of the palaeofield that lavas may not, but the notion that the information on the dipole field is somehow fundamentally more important (when it is only as large during reversals as the non-dipole field) is untenable.

It should be noted that experimental errors involved in sampling, orienting, demagnetizing and measuring the NRM are usually only a few degrees, unless the intensity is very weak, but a realistic circle of confidence of the VGP determined from a single core sample obviously cannot be estimated. However, if the VGPs from a series of samples at close stratigraphic intervals fall upon a smooth curve rather than being scattered in a chaotic manner, there is a reasonable case to be made that what is recorded is a global field rather than a magnetization process controlled by local factors. However, there are a number of possible ways in which magnetic recorders such as rocks and especially sediments may imperfectly or falsely record the changing magnetic field at the site. In some depositional environments, currents and/or living burrowing organisms may introduce a random element into the magnetization directions. For example, of the Miocene reversals from Crete in Laj *et al.*

(1988), the youngest gives VGPs scattered over the globe in contrast to the others, and this might be attributed to such processes.

4. Discussion of complexities in certain transitional records

It is hardly surprising that at the present stage in the study of transition fields, the palaeomagnetic records are to some degree confusing, as indeed they were in the initial development of palaeomagnetism when the evidence for geomagnetic reversals and continental drift were apparently contradicted by palaeomagnetic records through Phanerozoic time showing the geomagnetic field had always been directed to the present north. But these were shown to be remagnetized along the present field sometimes in the late Quaternary with records failing to reproduce the palaeofield (Runcorn 1956).

For instance, in the present discussion Clement (1991) and Bogue (1991) have argued that the VGP paths of the Brunhes–Matuyama transition from different sites do not agree. The data they discussed were from three sites. The VGP paths from the two midlatitude sites fell on the American preferred path, while the VGP path obtained from an equatorial site fell in Asia. They therefore concluded that the field was non-dipolar during this transition, and Clement (1991) proposed a model in which the field had a dominant octupole component. However, their argument is faulty. As records from two different sites agreed and fell on a path that was similar to the preferred paths in other reversals, this was *prima facie* evidence that the transition field was dipolar. These sites were not chosen so that the VGP paths would agree! Therefore as the VGP path from a third site did not agree, its reliability must be questioned. This will be discussed later.

Nevertheless, when the trail of VGPs fall in a simple curve on the globe serially with time, this is some evidence that what the sediment recorded was a changing global magnetic field, smoothed to some unknown degree by the magnetization process, rather than the effect of local environmental factors in the sedimentary process, which would not *a priori* be expected to have altered in such a way as to produce a smooth VGP path. However, the magnetization process takes time and the field is changing rapidly during a transition, so that it is possible that two magnetizations acquired at different times during the sedimentary process may be present and superposed. These two magnetization components, each stable but parallel to fields separated in time, add vectorially to give the observed natural remanent magnetization, and the corresponding VGP would, from such a sample, lie along a great circle joining the VGPs of the two fields. If the field reversed by rotating through 180° then the VGPs would still follow the longitudinal path, either monotonically or with some backtracking in the sedimentary sections where magnetization occurred in this way as we will discuss in more detail later. If this process is important then the detailed path of the VGPs is only in a general way the path of the Earth's axial dipole.

It is found in most of the examples discussed here that the VGP often moves along the preferred path but does not reach the antipode and returns to the original pole before starting to reverse again. It is debatable whether this 'backtracking' pattern is characteristic of the dynamo reversal process, although Glatzmaier & Roberts (1995) find such a behaviour in their dynamo calculations, or whether it is or not, as we have discussed, an artifact due to the sediment having been finally fixed in its magnetization at varying times after the actual deposition. In sediments, the magnetization is acquired from the ambient field and becomes 'permanent' when the expulsion of water from the spaces between grains prevents further rotation of the iron oxide particles by the field or when other diagenetic changes fix the magnetization. This may occur at various times after the deposition, depending on the size or shape distributions of the grains, the rate of deposition and geochemical alteration. These processes may well result in the recording of a field direction later than that at the time of initial deposition. Therefore two components of magnetization, each parallel to the ambient fields at two different times after deposition, held in iron oxide particles with different physicochemical properties, may be present in the NRM. Each component would have an intensity with a different ratio to the field intensity. Even if the dipole of the reversing dynamo rotated in one direction only along a path in one plane (the pole moving monotonically along a line of longitude during the process), the VGPs on these suppositions backtrack in the way most of the transitional records show. However, the data would still show that the pole of the reversing dynamo traversed one of the two preferred paths on the Earth's surface, because the primary and secondary magnetization components add vectorially. The phenomenon of backtracking is particularly important because if the above proposal is the correct explanation, rather than a characteristic of the core dynamo, it excludes the hypothesis that the field is non-dipolar during the transitions. For suppose that the two-component hypothesis is assumed to account for the backtracking. Only if the fields are dipolar both the components and the VGPs calculated from each add together vectorially. But a VGP calculated from the palaeomagnetic direction of a sample with two components from a non-dipolar field would not lie on the great circle joining the VGPs of each component. We emphasize therefore that, if the transition fields are non-dipolar, and the sediment records two field directions at different times during the transition, the primary and secondary magnetization components add vectorially, but the VGPs calculated from the samples would not lie on the same path as the VGPs calculated from the changing non-dipolar fields at different times during the transition. This argument is a critical one and perhaps should be set out exactly. Consider a geomagnetic field vector $\boldsymbol{F}_1$ and the corresponding dipole $\boldsymbol{M}_1$, and suppose that this field gives a primary magnetization to the sediment. Suppose later, a secondary magnetization is acquired from the field which has changed. Its vector is $\boldsymbol{F}_2$, and the corresponding geocentric dipole is $\boldsymbol{M}_2$. It cannot be assumed that the effectiveness of the two magnetization processes are the same, i.e. the primary remanent magnetization $\boldsymbol{I}_1 = k_1\boldsymbol{F}_1$ and the secondary remanent magnetization $\boldsymbol{I}_2 = k_2\boldsymbol{F}_1$ where k_1 is different from k_2. As field vectors and dipoles add vectorially, the total resultant magnetization of NRM is equal to $\boldsymbol{I}_1 + \boldsymbol{I}_2$ and will lie in the plane defined by $\boldsymbol{F}_1\boldsymbol{F}_2$ and the corresponding VGP will lie in the plane defined by $\boldsymbol{M}_1\boldsymbol{M}_2$. Because the colatitudes of the site referred by dipole $\boldsymbol{M}_1$ and dipole $\boldsymbol{M}_2$ will be different, and because a VGP is determined from the unit vector parallel to $\boldsymbol{I}$, the VGP will not be at the same angular distance from $\boldsymbol{M}_1$ as $\boldsymbol{I}$ will be from $\boldsymbol{F}_1$. Now suppose that the geocentric dipole $\boldsymbol{M}$, reversing by rotation, moves along a great circle (i.e. a preferred path) and $\boldsymbol{M}_1$ and $\boldsymbol{M}_2$ are its positions at times t_1 and t_2. Even if the magnetization process results in primary and secondary magnetization and $(t_2 - t_1)$ varies for different samples, the VGP may record spurious backtracking, but its path will be that of the rotating dipole. This argument does not apply if the transitional field is non-dipolar, as only dipoles add vectorially. Thus the preferred path, even if the sedimentary magnetization process is complicated as suggested, is consistent with the transitional field being dipolar and the Earth's dipole reversing by rotation along a preferred path. We conclude that, if the transitional fields are non-dipolar and the sediment records the superposition of two field directions at different times during the transition, the primary and secondary magnetization components add vectorially, but their VGPs do not. So if the transitional field was non-dipolar, the same preferred path would not have been found in different 'back track'. This superposition of magnetization may have been quite a general phenomena in sediments.

It has been widely held, e.g. by Van Hoof & Langerais (1991) that the preferred VGP paths found in sediments are artifacts, that is, that the sediments laid down during the time of transition between opposite polarities do not record the fields or record the fields too imperfectly to be useful, but recently it has been proven by Weeks *et al*. (1992) that when magnetization directions are properly cleaned to give single component directions, the preferential longitudes of reversal VGP paths will be due to field behaviour and not to an artifact of the magnetization process. The more important suggestion of an artifact (Van Hoof & Langereis 1991) is that the sediment, gradually deposited before, during and after the transition time, recorded a primary component along the previous stable field direction, diminishing as sedimentation proceeded, and then after the reversal took place, a secondary component along the new stable field direction was acquired by the sediment, of lower intensity in the older and therefore more compacted 'transition' sediment than in the younger. If it is then supposed that the mean stable fields were not exactly at 180° apart but were at an obtuse angle, defining a plane in which the VGPs of the 'transitional' samples lie. Thus the transitional fields, whatever they were, are not recorded in the transitional samples.

Thus it is possible that the transition directions may record (from various hypotheses concerning the 'fixing' of the magnetization) a superposition of the two stable, approximately axial dipole fields, reversed and normal, thus giving a longitudinal transitional field path, because of long-lived non-axial components producing small but fixed deviations from an axial dipole just before and just after the polarity transition. However, while there is a fundamental reason why the stable axial dipole may either be parallel or antiparallel to the axis of rotation, we do not know any such fundamental reason why the quasi-stable equatorial dipoles postulated in this suggested explanation of the preferred paths are antiparallel.

Inclination error has been demonstrated in laboratory experiments: depositional remanent magnetization may sometimes have an angle of magnetic inclination less than that of the ambient field as a disc or elongated particles, magnetized along their lengths, tending to settle in the horizontal. However, in the issue of the reality of preferred paths, for those records in which the VGPs move along similar paths, when observed from widely separated sites, inclination error cannot in general be important, but may add to scatter, also, all the records selected and presented here in our discussion are characterized by a lack of an inclination error because the stable fields of both polarities have means at 180° apart and inclinations which agree with the dipole formula for that latitude. It is entirely implausible that this phenomena is only important during the transitional behaviour of the geomagnetic field, but Quidelleur *et al*. (1995) claim that for the weaker fields during transitions it may become important.

This hypothesis concerning the stable fields has no observational support, but it must be noted that if the VGP path through the Americas during transition is to be entirely explained by an artifact. The non-axiality of the stable fields must have been due to the presence of an equatorial dipole component in addition to the axial dipole, which was directed towards the Americas if the North American–South American preferred path is to be explained and to Asia to explain the Australian–Asian preferred path, and not to steady non-dipolar components, such as the four persistent lobes in the field that were claimed to have existed in historic times (Gubbins 1987; Gubbins & Bloxham 1987) and in Cenozoic times (Gubbins & Kelly 1993). For if these non-dipole components dominate in the magnetizations of the transition zone, the VGPs calculated from sediments from widely different sites would not fall into narrow longitudinal sectors.

Of course no one doubts that over times that are long compared to the transition intervals and short compared to the intervals between reversals or excursions, sediments record mean palaeomagnetic directions in agreement with the mean palaeomagnetic directions of lavas, corresponding in the late Tertiary and Quaternary as was first demonstrated in ocean bottom cores by Opdyke (1972). The question at issue has been how reliable are the transition records in sediments, and we have concluded that scepticism has been much overstated. In the rest of this paper we discuss a group of sedimentary records which *prima facie* seem to give reliable information about polarity transitions. As in all palaeomagnetism, the ultimate test is the consistency of the data obtained from widely separated sites.

5. Analysis and interpretation of selected transitional records: reality of preferred paths

The twenty sections discussed here are those where the sampling was in greater detail than others in an attempt to obtain high resolution of the (geologically speaking) rapidly changing transition fields and are listed in table 1. The sedimentation rates of the sections recording these reversals range from low to high and are given in table 1. Thus each sample, usually 1 cm thick, carries a post-depositional remanent magnetization (PDRM) averaged over a time from 10^2–10^3 yr thus some of the secular variation is smoothed out. It is obvious that the low sedimentation rate cores cannot be high-resolution records of the Earth's magnetic field, and it is a fundamental error to expect a corresponding geomagnetic field averaged over a few thousand years to provide much evidence of the transitional field, but it still is important to test whether a wide variety of records tend to show similar characteristics of the VGP paths. The records under discussion are characterized by high palaeomagnetic stability, both in the samples of the transition zone and of the normal and reversed fields adjacent in time, and most of them, if not all, after cleaning, give single component final palaeomagnetic directions.

To compare the transitional records of a particular reversal or reversals from different sites a sequence of VGPs are calculated from the directions of remanent magnetization of each sample, using the dipole formula. Stratigraphic height in the core or section unfortunately cannot be assumed to be simply proportional to time even in ocean sediments and is definitely not to be expected in continental sediments. Therefore the dating of each sample at a site is not of course precise enough to allow correlation of individual VGPs in the records of the same transition at different sites. We display these reversal records in figures 1–14 as VGPs calculated from each sample.

The palaeomagnetic records of the Olduvai, Jaramillo, Blake and Pringle Falls polarity transitions, shown in figures 1–5, 8–12 are especially relevant in studying the reversal process, even though the geographical distribution of the sites is necessarily limited. The VGPs from each of the reversal records of the Upper Olduvai and Jaramillo subchrons, the Blake and Pringle Falls geomagnetic polarity episodes, when plotted in geographical coordinates (figures 1–5, 8–12) indicate that the seven Northern Hemisphere records have VGP paths that lie along the same longitudinal band roughly centred on the Americas. The VGP paths (Clement & Kent 1987; Herrero-Bervera *et al.* 1989) from core DSDP 609B for the Upper Olduvai (figure 9*a*) and the Blake and Pringle Falls episodes (figures 1–4) also show intermediate VGPs centred on the antipodal longitudinal band (Australia–East Asia). We suggest that these should be considered together, although two are termed Chrons and four are Subchrons, the latter being distinguished from the former by the short time in which the field is axial before reversing again, of the order of the short time during which the polarity reverses. Although they are usually distinguished, the dynamo seems to be behaving similarly in the two cases, especially if backtracking is a feature. We do not assert that the dynamo does not act differently at a Chron boundary from that at a Subchron boundary, but rather that, at this stage of the argument, we make no assumption that it does: thus we use the term 'reversal' (of polarity) in both cases.

We conclude that the agreement between these VGP paths from the Pacific Ocean and the North American continent with those from the Mediterranean prove that a predominantly dipolar field existed during the Olduvai, Blake and Pringle Falls, and presumably during the Jaramillo transitions. Perhaps of the greatest significance is the Blake record in which the VGP path moves from N to R over the Americas, but the path of the pole during its return to the normal polarity moves across the Pacific from South America to return to N along the Asian path. This remarkable behaviour in which, during a single reversal, both preferred paths are observed could hardly be accepted, were it not for the fact that it is observed from widely separated sites. Figures 3*a*, *b* show two of a number of sections through the lake sediments from Oregon—these about 20 km apart—where very similar records are found and these are very similar to the path found from the Eastern Mediterranean. Some similarity is evident in the presumed Pringle Falls episode from Long Valley, California shown in figure 2, although the first part of the path does not lie over North America and has been shown to be the earliest part of the episode fully exposed at Pringle Falls (Herrero-Bervera *et al.* 1994).

Recently the North American Oregon reversal has been redated as 218±10 ka (Herrero-Bervera *et al.* 1994) but because of this unique feature we tentatively continue to regard them as a different reversal, with the question of the radioactive age date to be resolved later.

The same conclusion about the reality of preferred paths has been reached by direct comparison of records of the Upper Olduvai transition from Italy (figure 8) (Tric *et al.* 1991*a*) and from two sites 2000 km apart in the Pacific Ocean (Herrero-Bervera & Khan 1992). The conclusion that the Upper Olduvai involves a rotation of the dipole along the Americas preferred path appears to be contradicted by two earlier records by Clement & Kent (1986) assigned as Upper Olduvai. One from the north Atlantic DSDP 609B which shows the VGPs following successively both the Americas and the Asian preferred paths (figure 9*a*), and one from the Indian Ocean RC14-14 (figure 9*b*) giving a totally different and more complex VGP path. If these two records are truly contemporaneous, they would, if taken without reference to other records, prove that the field was non-dipolar during this transition and this was then the conclusion reached by Clement & Kent (1986). One obvious interpretation of figure 9*a* is that the Australian–East Asian path and the American path were successive parts of the complete Upper Olduvai Subchron, even though only one path was recorded in each of the other records. This seems now to be the case with some adjustment in the assigned date as in figure 12 for the Lower Olduvai gives the Australia East Asian path as well as the Americas.

We have seen that the record RC14-14 from the Southern Hemisphere, does not fit this pattern, namely, its VGP path is anomalous. We must now address the question whether this record is of special significance because it comes from the Southern Hemisphere. Does it suggest that the conclusions reached so far, on the basis of Northern Hemisphere sites, are unsound? We think not. More records from the Southern Hemisphere are obviously desirable, but the extensive study of normal and reversed fields, their intensities, their secular variation, their average deviation, etc., have revealed no evidence that the core dynamo has any bias towards one polarity or the other. Therefore, how could records from the two hemispheres give different scenarios? We must examine other explanations. We raised doubt that the palaeomagnetic directions in a deep-sea core are in every case faithful records of the ambient magnetic field at the time of deposition, composition and cementation. It is possible, as we have emphasized, that some records may be greatly influenced by the depositional environments. It is certain that the rapid changes, geologically speaking, in the transition fields may be imperfectly recorded in gradually compacting sediments.

Other evidence arguing for non-dipolar transition fields has been presented. Three records of the Jaramillo Subchron are given by Clement & Martinson (1992) that show the field to be dipolar during this transition because the path is very different from that given above in figure 4. However, this record from Tahiti consists of a number of poles at high latitudes near both the North and South poles, but with no poles in low latitude. The path is therefore poorly defined and a similar result is found for a piston core from the southwest Indian Ocean core RC14-14, which also records the Upper Olduvai. Possibly the sampling in this core does not give a well-defined path and could only be said to be in agreement with the former results at high latitude.

We draw four conclusions from the data as follows.

(i) The palaeomagnetic records that show the strongest association with the two longitudinal sectors of North and South America and of Australia and East Asia, are the ones in which it has been possible to sample at frequent stratigraphical intervals (e.g. figures $3a, b$ and figure 8). In general, but not invariably, samples stratigraphically adjacent give VGPs close together so that the pole paths from a section form a sequence in time.

In the above discussion VGPs are seen to move progressively from one pole to the other, but it is very significant that the paths during backtracks, common in the records, follow roughly the same path; although records from different sites of a single reversal do not usually show the same number of backtracks, for all tracks may not be recorded. But if the transitional fields are predominantly dipolar, we conclude that the palaeomagnetic recorder is giving a reasonably faithful record of the ancient field.

This is evidence that the physico–chemical processes in the sedimentary process resulting in magnetization are recording a global rather than a local phenomenon: the individual observations of the transitional field, in this case the VGPs, migrate from one polarity to the other polarity in an organized rather than in a chaotic way. The coincidence of the VGP paths for the different reversals from widely separated parts of the world strongly supports the hypothesis that at least these reversals occur by the rotation of the dipole, though generally with a decrease in its moment.

(ii) The records of the Blake and Pringle Falls events from the widely separated sites of the East Mediterranean and Oregon in North America (see figures 1–4) give essentially the same VGP paths. Thus we can be confident of its most significant feature during the return from R to N, which is that in the last part of the Blake geomagnetic polarity episode, the VGP path moved first to the midsouthern latitudes over South America and then across the Pacific to conclude its transition to normal polarity along the Asian preferred path. In one reversal, the association of the VGPs with both preferred longitude sectors is compelling evidence that some mechanism involving mantle–core interactions guides the reversing dipole in one or other of these paths.

(iii) It is a noteworthy feature of many records that before or after the VGP moves from one pole to the other, many minor VGP movements occur in a much greater spread of longitudes than during the main transition. This feature is very clear in the Blake and Pringle Falls records (figures 1, $3a, b$) in the Cobb Mountain event (figure 7), and in the Upper Olduvai (figure 8). This may be important in the discussion of the influence of the mantle on the transitions but is itself an argument that the sediments are faithfully recording the changing ambient-geomagnetic field at the site. It is when the mean field corresponds to a dipole along the Earth's axis that the short term changes in the field, whether due to the changing non-dipole components or to the growth and decay of equatorial dipoles must, by considerations of symmetry, result in a wide spread of the VGP longitudes.

(iv) Some records of the transition fields do not so clearly fit into the simple hypothesis formulated above. Although there is no theory of how the core dynamo reverses, it appears that the dominance of the Coriolis force in the magnetohydrodynamic equation of core motions accounts for the stable axial field (Runcorn 1956). But the basic equation implies, because it is linear in the field, that the same motions in the core could support axial dipole fields of opposite polarity. Some changes in core motions therefore could initiate the transition. The problem is that we simply do not know the 'activation barrier' for a reversal, nor do we know whether there are substantial changes in fluid motions on relevant time scales. Glatzmaier & Roberts (1995) do find such changes. No such fundamental argument excludes the possibility that the reversal may occur in different ways on different occasions. The prospect of studying every reversal is daunting! We know that deep-sea records are able to provide very detailed records of field changes, provided that the magnetization process has high fidelity and the sedimentation rate is rapid and constant (Weeks *et al.* 1988, 1992).

The interesting and surprising result of many of these reversal records is the repetition of the confinement of the VGP paths over the Americas and its antipode obtained from sediments deposited in different geological environments, from different and widely separated geographical regions with quite different lithologies and magnetic mineralogies, and most importantly, sedimentation rates which varied over nearly two orders of magnitude. However, it does appear that over recent geological times, from the random sampling of reversals that have been made, the two preferential sectors of longitude for transitional VGPs is a reasonable working hypothesis concerning one of the most fascinating phenomena in the interior of the Earth.

6. The significance of certain anomalous VGP paths

We now turn to a discussion of certain anomalous records in which the VGPs do not follow the preferred paths, but which appear to faithfully record the transitions.

We consider that they are the 'exceptions that prove the rule'. In this discussion the transitional fields during the Cobb Mountain reversal (1.1 Ma) are of particular interest. Clement & Martinson (1992) and Clement (1992) showed that two sedimentary cores from the north Atlantic gave VGP records which, apart from the initial and final rebounds near the South geographical pole, showed that the pole moved from R to N over the Pacific near a longitude centred on 180°, and from N to R over the Atlantic near a longitude centred about 0°. As the two sites are only about 15° apart, the transitional field cannot be accepted as dipolar on these data alone. However, Clement & Martinson (1992) showed that volcanic records from Tahiti (Chauvin *et al.* 1990), though only sampling a fraction of the transition time, gave VGPs which fell near the R–N path determined from much more continuously deposited sediments. Further, Clement (1992) showed that two cores from the western Pacific gave VGP tracks which were in substantial agreement with those from the north Atlantic sites. Thus, he concluded that the transitional fields during the Cobb Mountain reversals were dipolar. However, it is even more significant that the preferred paths, though confined in longitude, do not agree with the familiar 'preferred' Americas and Australia–East Asia paths, but lie about 90° between them. A path with some similarity is observed from the Gauss–Matuyama N to R transition recorded at Searles Valley, California (Liddicoat 1982) as shown in figure 14, it goes from N–R near the mid-Atlantic near and then goes to the South pole in South America. The record of this same reversal from Argentina (Ruocco 1991) shown in figure 13 is more scattered but is not inconsistent with that from the Northern Hemisphere site (i.e. the first part of the path from N to R is in the Atlantic and the rest of the path is centred over South America).

The new phenomenon these researchers have discovered had in fact already been seen in earlier transition records but was not then regarded as significant. The study by Laj *et al.* (1988) of three successive polarity reversals in the Miocene from Zackinthos (Greece) showed that in the two younger reversals the VGPs moved from R to N and N to S (with backtracking) along the Australia–East Asia preferred path, even though the sampling did not allow these paths to be well defined. Only in the light of the later, and with more detailed sampling of the transition fields can these reversals be recognized as occurring along preferred paths. The oldest of the three reversals from Zackinthos from N to R consists of three main 180° swings, although the first is tenuously defined by only two samples. In the second and third swings the VGPs move across South America, but significantly, in view of our discussion of the Cobb Mountain record, the VGPs moved from the N pole and then for a large number of stratigraphically adjacent specimens the VGPs clustered about Europe, around longitude 0° before moving on to the S pole by the preferred path in South America. Either a considerable fraction of the time of this transition is spent in the longitude midway between the two preferred paths, or the sedimentary rate happens to be very fast for this stratigraphic interval. A further example of a tendency to favour a midway path is found in the work of Valet *et al.* (1988) who studied five different but consecutive polarity transitions in the Miocene from Crete. In two R to N transitions at 7.25 Ma and 5.87 Ma the VGPs very clearly crossed the Americas, while for the N to R transition at 6.34 Ma the VGPs equally clearly preferred the Australia–Asia path. However, for the N to R transition at 5.57 Ma the VGPs moved across the Atlantic over a confined longitudinal sector halfway between the two preferred paths. We conclude that Clement & Martinson (1992) (see figure 7) and Liddicoat 1982 (see figure 14) have discovered a complicating, but perhaps very significant, feature of the rotating dipole reversal process: that a path midway between the normal preferred paths is sometimes followed. We think that this is a very important finding that has not been hitherto pointed out in the discussion of the significance of preferred paths, because it has been observed in only a few transitional records. This is not an exception that proves the rule but we consider it important.

7. Theories on the role of the mantle in polarity transitions

In searching for an explanation for the restriction of the paths of the transitional poles to the two longitudinal sectors, it is natural to look for correlations between them and variations of properties in the lower mantle and at the core–mantle interface. The first question to be asked is whether the detailed global pattern of the main geomagnetic field over historic time suggests any special relation of the observed field with the two preferred longitudinal zones. It has been shown from data back to 1700 that the non-dipole field since that time has persistent features at the core–mantle interface called main lobes. One pair is located beneath northwest Canada and west Antarctica, and the other pair is beneath east Siberia and east Antarctica (Bloxham & Gubbins 1985). It is important to underline the fact that these main lobes are in the total field at the core–mantle boundary and not the non-dipole field and are not evident at the Earth's surface. These lobes lie rather near the Americas and Asian paths of the transition poles. If these field lobes have been present over the last 10 Ma, as Gubbins & Kelly (1993) maintain, they would perhaps be explained by the diffusion of the temperature variations over horizontal surfaces in the lower mantle, inferred from seismic tomography, into the core. These could then be supposed to control the dynamo process so that it generates magnetic anomalies at these longitudes in the northern and southern high latitudes. Laj *et al.* (1991, 1992, 1993) have drawn attention to a correlation between the two preferred paths and the roughly longitudinal bands of high P-wave velocities determined by seismic tomography (Dziewonski & Woodhouse 1987; Giardini *et al.* 1987; Morelli & Dziewonski 1987). The latter are interpreted as low-temperature anomalies associated with mantle convection, which therefore would have existed for 10^3–10^8 years. In their analysis of historical observations carried back to 1700, Bloxham & Gubbins (1985) could follow the westward drift of the non-axial parts of the geomagnetic field between 90°E and 90°W in the non-Pacific hemispheres, but this drift does not manifest itself in the Pacific hemisphere. Bloxham & Jackson (1991) interpret this using the frozen flux theorem, as a strong westward flow from 90°E–90°W at low latitudes, and to explain its absence in the Pacific hemisphere, they invoke partly the influx of fluid from higher latitudes and partly upwelling in low latitudes around 90°E and down going around 90°W. This is essentially a model deduced from the geomagnetic secular variation by Courtillot *et al.* (1978). Further, Laj *et al.* (1991, 1992*a*, *b*, 1993) point to the fact that the preferred paths are found in the area beneath the Pacific when the surface flow velocities in the core are markedly smaller than elsewhere. Gubbins (1987) thus concluded that the mantle temperature anomalies are influencing the core dynamo and controlling the particular way the field reverses. These ideas have not been worked out in any detail because the dynamo theory has not been developed much beyond kinematic models. Further, the interpretation of tomography in term of temperature anomalies can be faulted (Runcorn 1993).

Another explanation of the preferred paths does not involve an understanding of how the dynamo reverses: it accepts that this occurs by the rotation of the dipole.

Runcorn (1992) attaches fundamental significance to the fact that the preferred paths lie on the west and east side of the Pacific Ocean over which the geomagnetic secular variation and the non-dipolar field are known from historical data to have been smaller relative to the rest of the world by about one third. Returning to an old suggestion Runcorn (1956, 1992) argues that this does not reflect any striking difference between the vigorousness of the dynamo action between two hemispheres of the core, but results from the attenuation of shorter periods of the geomagnetic secular variation by a layer of near-metallic conductivity underneath the Pacific hemisphere. This screening, by a layer with an electrical conductivity roughly two orders of magnitude less than a metal in the lower mantle, is identified with the D'' layer, which seismologists have long known to be heterogeneous. The model proposed is that the D'' layer consists of a hemispherical shell of quasi-metallic conductivity below the Pacific, its boundaries being near the two preferred paths, while in the other hemisphere the D'' layer is insulating. This hemispherical asymmetry is attributed to greater amounts of FeO and FeS in the D'' layer below the Pacific. This theory of the preferred paths, accepting that the field reverses by rotation of the dipole, discusses the electromagnetic interaction between it and the conducting D'' hemispherical shell. The core dynamo, if alone in space, would not reverse its polarity on successive occasions by the pole following the same path (in a frame of reference rotating with the core): a fluid has no such memory. Consequently Runcorn (1992) supposes that, as the reversal begins, the dipole rotates initially in an arbitrary meridian. Now it is known from historical observations that the rotation of the core relative to the mantle about the Earth's axis changes, otherwise there would be no explanation for the irregular changes in the length of the day (Runcorn 1956). These decadal changes need to be distinguished from those on a shorter time scale of months and a year, strikingly explained by exchange of angular momentum between the atmosphere and the mantle (e.g. Hide 1993, 1996; Jackson *et al.* 1993; Jault & LeMouel 1988) using the much more accurate observations of the Earth's rotation by the new techniques of very long base interferometry (VLBI) and laser tracking of satellites. There is evidence that the rotation rate for the outer part of the core about the Earth's axis has varied over the last 150 y, as measured by the westward drift of the geomagnetic field, so that the angular momentum between core and mantle of the Earth as a whole has remained constant (apart from its small steady decrease due to tidal friction). The magnitude of the torque which transfers the angular momentum can be calculated from the astronomical data (Stephenson & Morrison 1984) and does not depend on whether electromagnetic torques are responsible or whether topography on the core–mantle interface is the cause as suggested by different scientists.

However, if the torques are electromagnetic in origin there is clear quantitative support for the following argument. The rotating dipole has, with respect to the hypothetical conducting hemispherical shell, three components: an axial one diminishing until the pole crosses the equator, an equatorial component in the bounding meridian of the shell, and an equatorial component in the midmeridian of the shell. Changes in the former two components do not result in a torque about the Earth's axis, but changes in the latter component induce electric currents in the shell which do produce a torque about the Earth's axis equal and opposite on the mantle and on the core. If the dipole moment is constant and its rotation uniform, the equatorial component increases rapidly until the pole reaches low latitudes. The component in the midmeridian of the shell induces electric currents that produce a nearly uniform magnetic field opposed in direction to it. This field produces a torque rotating the dipole until it lies in one of the bounding meridians of the shell. The VGP of the reversing field thus moves in one or the other preferred path. This hypothesis assumes that the core as a whole or its outer part rotates about the Earth's axis: this idea is also assumed during the shorter time scale processes of the irregular changes in the length of the day. We do not have a model of how the core dynamo reverses and what changes in the core motions are responsible, although these motions could be quite minor. Therefore in this hypothesis we assume the core rotates as a whole, but in the explanation of the decadal changes in the length of the day, the same assumption is made because in the complex core motions only the zonal odd harmonic has angular momentum about the Earth's axis.

It is known that core motions are responsible not only for the creation and destruction of lines of force of the Earth's magnetic field, but also for their rearrangement. The geomagnetic secular variation may be largely due to this rearrangement process, but according to Hide (1967) the creation and destruction of magnetic field lines cannot be ignored in the theory of slower field variations, including reversals in the sign of the dipole component of the main field. Also, Hide (1967, 1996), Bloxham & Gubbins (1987) and Gubbins & Richards (1986), recognized that owing to the Earth's rotation, quite weak horizontal temperature variations at the boundaries of the core and horizontally extensive topographical features of the core boundaries that are also shallow (vertical dimensions about a km or so, possibly even less, Hide (1993)) that would escape detection by modern seismological methods, might nevertheless produce pronounced hydrodynamical effects throughout the core (Hide 1966). Consequently, it is conceivable that the conditions prevailing at the core–mantle interface can be reflected in the main geomagnetic field and a complete theory of the preferred paths will obviously have to take these questions into account. A reviewer (Professor D. J. Stevenson) has indicated to us that the the physical model described above based on the arguments of Runcorn (1992), relies on the notion that the reversal can be thought of as a rotating dipole maintaining strength, which incidentally is exactly contrary to the preferred bands explanation for the failure of the lava data to give what it has been proposed. If instead, one adopted the perfectly reasonable view (compatible both with the data and dynamo theory) that the three Gauss coefficients (g_1^0, g_1^1, h_1^1) defining the dipole have separate evolution (differential) equations, then a reversal would consists of g_1^0 crossing zero without g_1^1 or h_1^1 undergoing substantial diminutions. There would then be no torque of the required kind to reorient the dipole to the preferred longitude. Now of course, it may not be that simple and perhaps there is some increasing in g_1^1 as g_1^0 crosses zero; but then we get to the more general point which is that without some knowledge of what is actually occurring during a reversal (i.e. the new flux being created in the core?), it is impossible to predict even the sign of the electromagnetic torque let alone whether it might be enough to do the job. This is a very weak model to be invoked, even though there can be no doubt that the relative lack of secular variation in the Pacific needs to be explained. Also according to Stevenson (personal communication, 1996) the arguments for a high conductivity D'' in some places are not based on any physico–chemical model, despite the fact that there are arguments by several workers for 100 km structures based on micron-scale experiments. It is, of course, very reasonable to suppose conductivity anomalies just above the core mantle boundary (CMB); the unreasonableness lies in the claim that they might be 100 km thick.

Although we have discussed the evidence that in the majority of cases the VGPs move during reversals along these preferred paths, we have drawn attention to certain exceptions particularly the Cobb Mountain reversal, where the paths lie midway between the preferred paths. We have stressed their significance, and the question arises whether these exceptions are a clue to the correct explanation of the role of the mantle. It has been argued that the key to the explanation of why the VGPs move along these preferred paths is that they correlate with the two high P-wave anomalies in the lower mantle also lying along longitudinal sectors beneath the Americas, Australia and East Asia. The usual interpretation of mantle tomographical anomalies is that they are density anomalies associated with mantle convection and therefore are lateral variations in temperature, although Runcorn (1993) argues against this. These temperature anomalies are supposed to diffuse into the core and control the reversing dynamo in some way so that the VGPs are confined to the high P-wave anomaly sectors of the mantle. However, the exceptional paths of the VGPs are of great significance, as we have pointed out, because they are clearly not explained in this theory as presently formulated and we think argues against its correctness.

Does the alternative outlined above (in which the dipole, and therefore the core, is rotated about the Earth's axis until the pole is moving in the bounding meridian of the conducting shell) offer any possibility of explaining these exceptional cases? It is a general observation that the palaeointensity is reduced by a factor of three to five during reversals, although exact determinations in the case of sediments are well known to be difficult to obtain, as we have stated above. If the dipole moment diminishes, then, especially when the pole is in low latitude, the equatorial dipole component may diminish—the effect of the rotation of the dipole being outweighed by the decrease in the moment. Thus the induced currents in the hemispherical shell are reversed and the induced magnetic field of the shell points in the direction of the equatorial dipole component, producing a torque which rotates the dipole towards the midmeridian of the shell.

McFadden (1992) pointed out that temporal variations in the spatial properties of D'', and of the core–mantle boundary, are responsible for many of the long term changes in the geomagnetic field. The palaeomagnetic records of the reversals therefore pose fundamental questions of the nature of lateral variations of property in the deep interior of the Earth (Laj *et al.* 1991, 1992, 1993). It is perhaps premature to ask why the dynamo reverses by the dipole rotating through 180°. More examples and better palaeointensity measures are needed before this can be addressed with confidence (McFadden *et al.* 1993).

We must emphasize that this interpretation, however, does *not* mean that other harmonic components are non-existent in the transitional field or that other geomagnetic reversals (not studied here) are also controlled by a predominantly dipolar field. It is, in fact, quite conceivable that each geomagnetic reversal may have its own characteristics of the controlling geomagnetic transitional field; for example, see the recent interpretations for the Matuyama–Brunhes reversal records (Clement & Kent 1991; Clement 1991). But the results discussed in this paper show very clearly the importance of the morphology of the transitional geomagnetic fields for geodynamics. Many more records of these and other reversals without a well-spaced distribution in space and time will be needed to give a full picture of this complex phenomena of reversals. But the records presented in this discussion, we believe show that significance can be attached to the preferred location of the transitional VGP paths for many reversals. They are obtained from different sites randomly chosen and widely spaced on the Earth's surface: from deep-sea sediments, lake sediments, and sedimentary rocks deposited in rather different geological environments with different lithologies, magnetic mineralogies and sedimentation rates. We believe that the records correctly but not fully describe the essential behaviour of the Earth's magnetic field during some polarity transitions selected randomly over the last quarter of Cenozoic times. The discovery of the preferred paths has stimulated a search for a link between the transitions and the behaviour of the core dynamo. Constable (1992) claims to have found a 'bias' of the core dynamo towards the preferred path longitudes. She calculated the VGPs from 2000 spot readings of the geomagnetic field over the last 5 Ma and found that the histogram of their longitudes peaked at the preferred paths. She interpreted this as showing that the core dynamo, even when producing stable fields of both normal and reversed polarity, has this bias. But Runcorn (1993) argued that the peaks are an artifact of the dipole formula because the sites of the lavas sampled are grouped around the 0° (the North Atlantic province) and nearly 180° longitude away in Hawaii. Nevertheless these palaeomagnetic transition paths are stimulating new directions to studies of the core dynamo.

Financial support for this study to E.H.-B. was provided by the SOEST-Hawaii Institute of Geophysics and by National Science Foundation Grants EAR-8916597, EAR-9114305, EAR-9018270 and EAR-908302 and EAR-9508302 to E.H.-B. We would like to express our special thanks to Dr Bradford Clement and Dr D. V. Kent for providing us with the necessary data from cores RC14-14 and DSDP 609B. Also we thank Professor D. J. Stevenson and two anonymous reviewers for their constructive and knowledgeable help during the writing of this paper. SOEST contribution number 4505, HIGP contribution number 946.

References

Bloxham, J. & Gubbins, D. 1985 The secular variation of the Earth's magnetic field. *Nature* **317**, 777–781.

Bloxham, J. & Gubbins, D. 1987 Thermal core–mantle interactions. *Nature* **325**, 511–513.

Bloxham, J. & Jackson, A. 1991 Fluid flow near the surface of Earth's outer core. *Rev. Geophys.* **29**, 97–120.

Bloxham, J. 1993 Mapping the magnetic field at the core–mantle boundary: constraints on the geodynamo. *Geol. Soc. Am. Today* **3**, 221–250.

Bogue, S. W. 1991 Reversals of opinion. *Nature* **351**, 445–446.

Bogue, S. W. & Coe, R. S. 1984 Transitional paleointensities from Kauai, Hawaii and geomagnetic reversal models. *J. Geophys. Res.* **89**, 10 341–10 354.

Chauvin, A., Roperch, P. & Duncan, R. A. 1990 Records of geomagnetic reversals from volcanic islands of French Polynesia. II. Paleomagnetic study of a flow sequence (1.2–0.6 Ma) from the island of Tahiti and discussion of reversal models. *J. Geophys. Res.* **95**, 2727–2752.

Clement, B. M. 1991 Geographical distribution of transitional VGPs: evidence for non-zonal equatorial symmetry during the Matuyama–Brunhes geomagnetic reversal. *Earth Planet. Sci. Lett.* **104**, 48–58.

Clement, B. M. 1992 Evidence for dipolar fields during the Cobb Mountain geomagnetic polarity reversals. *Nature* **358**, 405–407.

Clement, B. M. & Kent, D. V. 1984 A detailed record of the lower Jaramillo polarity transition from a Southern Hemisphere deep-sea sediment core. *J. Geophys. Res.* **89**, 1049–1058.

Clement, B. M. & Kent, D. V. 1985 A comparison of two sequential geomagnetic polarity transitions (upper Olduvai and lower Jaramillo) from the Southern Hemisphere. *Phys. Earth Planet. Int.* **39**, 301–313.

Clement, B. M. & Kent, D. V. 1986 In *Geomagnetic polarity transition records from five hydraulic piston core sites in the North Atlantic* (ed. W. F. Ruddiman, R. Kidd, E. Thomas *et al.*), Init. Reports DSDP, no. 94, pp. 831–852. Washington, DC: US Government Printing Office.

Clement, B. M. & Kent, D. V. 1987 Short polarity intervals within the Matuyama: transitional field records from hydraulic piston cored sediments from the North Atlantic. *Earth Planet. Sci. Lett.* **81**, 253–264.

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

Clement, B. M. & Kent, D. V. 1991 A Southern Hemisphere record of the Matuyama–Brunhes transition. *Geophys. Res. Lett.* **18**, 81–84.

Clement, B. M. & Martinson, D. G. 1992 A quatitative comparison of two paleomagnetic records of the Cobb Mountain subchron from North Atlantic deep-sea sediments. *J. Geophys. Res.* **97**, 1735–1752.

Coe, R. S. & Prévot, M. 1989 Evidence suggesting extremely rapid field variation during a geomagnetic reversal. *Earth Planet. Sci. Lett.* **92**, 292–298.

Constable, C. 1992 Geomagnetic reversals, paleosecular variation, and core–mantle boundary conditions, *EOS* **73**, 103.

Courtillot, V., Ducruix J. & Le Mouel, L. L. 1978 Sur une acceleration recente de la variation seculaire du champ magnetique terestre. *C. R. Hedb. Seances Acad. Sci.* D **287**, 1095–1098.

Creer, K. M. & Ispir, Y. 1970 An interpretation of the behaviour of the geomagnetic field during polarity transitions. *Phys. Earth Planet. Int.* **2**, 283–293.

Creer, K. M., Readman, P. W. & Jacobs, A. M. 1980 Palaeomagnetic and Palaeontological dating of a section at Gioia Tauro, Italy: Identification of the Blake Event. *Earth Planet Sci. Lett.* **50**, 289–300.

Dziewonski, A. M. & Woodhouse, J. 1987 Global images of the Earth's interior. *Science* **236**, 37–48.

Fuller, M. 1989 Fast changes in geomagnetism. *Nature* **339**, 582–583.

Fuller, M., Williams, I. & Hoffman, K. A. 1979 Paleomagnetic records of geomagnetic field reversals and the morphology of the transitional fields. *Rev. Geophys. Space Phys.* **17**, 179–203.

Giardini X. D., Li, J. H. & Woodhouse, J. H. 1987 Three-dimensional structure of the Earth from splitting in free-oscillation spectrs. *Nature* **325**, 405.

Glatzmaier, G. & Roberts, P. H. 1995 A three-dimensional self-consistent computer simulation of a geomagnetic field reversal. *Nature* **377**, 203–209.

Gubbins, D. 1987 Mechanism for geomagnetic polarity reversals. *Nature* **326**, 167–169.

Gubbins, D. & Richards, M. 1986 Coupling of the core dynamo and mantle: thermal or topographic? *Geophys. Res. Lett.* **13**, 1521–1524.

Gubbins, D. & Bloxham, J. 1987 Morphology of the geomagnetic field and implications for the geodynamo. *Nature* **325**, 510–511.

Gubbins, D. & Kelly, P. 1993 Persistent patterns in the geomagnetic field over the past 2.5 My. *Nature* **365**, 829–832.

Hammond, S. R., Seyb, S. M. & Theyer, F. 1979 Geomagnetic polarity transitions in two oriented sediment cores from the northwest Pacific. *Earth Planet Sci. Lett.* **44**, 167–175.

Herrero-Bervera, E. & Theyer, F. 1986 Non-axisymmetric behaviour of Olduvai and Jaramillo polarity transitions recorded in north-central Pacific deep-sea sediments. *Nature* **322**, 159–162.

Herrero-Bervera, E., Theyer, F. & Helsley, C. E. 1987 Olduvai onset polarity transition: two detailed palaeomagnetic records from North Central Pacific sediments. *Phys. Earth Planet. Int.* **49**, 325–342.

Herrero-Bervera, E., Helsley, C. E., Hammond, S. R. & Chitwood, L. A. 1989 A possible lacustrine paleomagnetic record of the Blake episode from Pringle Falls, Oregon, USA. *Phys. Earth Planet. Int.* **56**, 112–123.

Herrero-Bervera, E. & Khan, M. A. 1992 Olduvai termination: detailed palaeomagnetic analysis of a north central Pacific core. *Geophys. Jl Intl* **108**, 535–545.

Herrero-Bervera, E. & Helsley, C. E. 1993 Global paleomagnetic correlation of the Blake geomagnetic polarity episode. *Applications of paleomagnetism to sedimentary geology*, vol. 49, pp. 71–82. SEPM Special Publication. ?

Herrero-Bervera, E., Helsley, C. E., Sarna-Wojcicki, A. M., Lajoie, K. R., Meyer, C. E., Turrin, B. D., Donnelly-Nolan, J. M., McWilliams, M. O., Negrini, R. M. & Liddicoat, J. C. 1994 Age and correlation of a paleomagnetic episode in the western U.S. by ^{40}Ar/^{39}Ar dating and tephrachronology: The Jamaica, Blake or a new polarity episode? *J. Geophys. Res.* **99**, 24 091–24 103.

Hide, R. 1966 Free hydromagnetic oscillations of the Earth's core and the theory of geomagnetic secular variation. *Phil. Trans. R. Soc. Lond.* A **259**, 615–650.

Hide, R. 1967 Motions of the Earth's core and mantle, and variations of the main geomagnetic field. *Science* **157**, 55–56.

Hide, R. 1993 Angular momentum transfer between the Earth's core and the mantle. In *Dynamics of Earth's deep interior and Earth rotation*, pp. 109–112. Washington, DC: American Geophysical Union.

Hide, R. 1996 Waves and stationary patterns in the core and the interpretation of transition fields in geomagnetic polarity reversals, contribution to the proceedings of the discussion meeting on *Geomagnetic reversals: the transition fields and their interpretation, 14 January 1994, Royal Astronomical Society, London. Surv. Geophys.* **17**, 213–214.

Hillhouse, J. & Cox, A. 1976 Brunhes–Matuyama polarity transition. *Earth Planet. Sci. Lett.* **29**, 51–64.

Hoffman, K. A. 1977 Polarity transition records and the geomagnetic dynamo. *Science* **196**, 1329–1332.

Hoffman, K. A. 1982 The testing of geomagnetic reversal models: recent developments. *Phil. Trans. R. Soc. Lond.* A **306**, 147–159.

Hoffman, K. A. 1984 A method for the display and analysis of transitional palaeomagnetic data. *J. Geophys. Res.* **89**, 6285–6292.

Hoffman, K. A. 1986 Transitional behaviour from Southern Hemisphere lavas: evidence for two-stage reversals of the geodynamo. *Nature* **320**, 228–232.

Hoffman, K. A. 1991 Long-lived transitional states of the geomagnetic field and the two dynamo families. *Nature* **354**, 273–277.

Hoffman K. A. & Fuller, M. 1978 Transitional field configurations and geomagnetic reversal. *Nature* **273**, 715–718.

Hospers, J. 1953 Reversals of the main gomagnetic field. I. *Proc. Kon. Nederl. Akad. Wet.* B **56**, 467–476.

Jackson, A., Bloxham, J. & Gubbins, D. 1993 Time-dependent flow at the core surface and conservation of angular momentum in the coupled core–mantle system. In *Dynamics of the Earth's deep interior and Earth rotation* (ed. J.-L. LeMouel *et al.*), pp. 97–107. American Geophysical Union Monograph.

Jault, D., Gire, C. & LeMouel, J.-L. 1988 Westward drift, core motions and exchanges of angular momentum between core and mantle. *Nature* **333**, 353–356.

Kaiser, A. D. & Verosub, K. L. 1985 Modelling polarity transitions with radial dipole sources: geomagnetic field behavior at northern midlatitudes. *Geophys. Res. Lett.* **72**, 777–780.

Laj, C., Guitton S., Kissel, C. & Mazaud, A. 1988 Complex behaviour of the geomagnetic field during three successive polarity reversals, 11–12 My B.P. *J. Geophys. Res.* **93**, 11 655–11 666.

Laj, C., Weeks, R. & Fuller, M. D. 1989 Observations and models of reversal transition fields. In *Geomagnetism and palaeomagnetism* (ed F.J. Lowes *et al.*), pp. 185–203. NATO Advanced Science Institute Series.

Laj, C., Mazaud, A., Weeks, R., Fuller, M. D. & Herrero-Bervera, E. 1991 Geomagnetic reversal paths. *Nature* **351**, 447.

Laj, C., Mazaud, A., Fuller, M. D., Herrero-Bervera, E. & Weeks, R. 1992*a* Lateral variations at the Core-Mantle boundary revealed by geomagnetic reversal paths obtained from sedimentary rocks. *The 3rd SEDI Symp. Core–Mantle Boundary Region: Structure and Dynamics. Paleomagnetic Inferences about the Dynamo Process, Mizusawa, Japan*, p. 67.

Laj, C., Mazaud, A., Weeks, R., Fuller, M. & Herrero-Bervera, E. 1992*b* Statistical assessment of the preferred longitudinal bands for recent geomagnetic reversal records. *Geophys. Res. Lett.* **19**, 2003–2006.

Laj, C., Mazaud, A., Fuller, M. & Herrero-Bervera, E. 1993 Preferred bands of longitude for geomagnetic reversal VGP paths: implications for reversal mechanisms. In *Flow and creep in the solar system: observations, modelling and theory* (ed. D. B. Stone & S. K. Runcorn), pp. 121–129. Amsterdam: Kluwer.

Liddicoat, J. C. 1982 Gauss–Matuyama polarity transition. *Phil. Trans. R. Soc. Lond.* A **306**, 121–128.

Liddicoat, J. C. & Bailey, R. A. 1989 Short reversal of the paleomagnetic field about 280 000 years ago at Long Valley, California. In *Geomagnetism and paleomagnetism* (ed. F. J. Lowes *et al.*), pp. 137–153. Kluwer.

Liddicoat, J. C. 1990 Aborted reversal of the paleomagnetic field in the Brunhes Normal Chron in east-central California. *Geophys. Jl Int.* **102**, 747–752.

Linsen, J. H. 1991 Properties of Pliocene sedimentary geomagnetic reversal records from the Mediterranean. *Geologica Ultraiectina* **80**, 1–231.

Mankinen, E. A., Prévot, M., Grommé, C. S. & Coe, R. S. 1985 The Steens Mountain (Oregon) geomagnetic polarity transition. I. Directional history, duration of episodes, and rock magnetism. *J. Geophys. Res.* **90**, 10 393–10 416.

McFadden, P. 1992 Paleomagnetic constraints: problems and possibilities, paleomagnetic inferences about dynamo process. *The 3rd SEDI Symp., Core–Mantle Boundary Region: Structure and Dynamics Mizusawa, Japan*, pp. 68–70.

McFadden, P. L., Barton, C. E. & Merrill, R. T. 1993 Do virtual geomagnetic poles follow preferred paths during geomagnetic reversals? *Nature* **361**, 342–344.

Merrill, R. T. & McFadden, P. L. 1990 Paleomagnetism and the nature of the geodynamo. *Science* **248**, 345–350.

Morelli, A. & Dziewonski, A. M. 1987 Topography of the core–mantle boundary and lateral homogeneity of the liquid core. *Nature* **325**, 678–683.

Opdyke, N. D. 1972 Palaeomagnetism of deep-sea cores, *Rev. Geophys. Space. Phys.* **10**, 213.

Prévot, M. & Camps, P. 1993 Absence of preferred longitude sectors for poles from volcanic records of geomagnetic reversals. *Nature* **366**, 53–56.

Prévot, M., Mankinen, E. A., Coe, R. S. & Grommé, S. 1985 The Steens Mountain (Oregon) geomagnetic polarity transition. II. Field intensity variations and discussion of reversal models. *J. Geophys. Res.* **90**, 10 417–10 488.

Quidelleur, X., Holt, J. & Valet, J.-P. 1995 Confounding influence of magnetic fabric on sedimentary records of a field reversal. *Nature* **374**, 246–249.

Rais, A., Surmont, J., Gillot, P. Y., Blanchard, E. & Laj, C. 1991 A volcanic record of the Blake event: preliminary results from Reunion Island (France). *EOS* **72**, 139.

Runcorn, S. K. 1955 Core motions and reversals of the geomagnetic field. *Annales Geophysique* **11**, 73–79.

Runcorn, S. K. 1956 The magnetism of the Earth's Body. *Handbuch Physik* **47**, 498–533.

Runcorn, S. K. 1992 Polar path in geomagnetic reversals. *Nature* **356**, 654–656.

Runcorn, S. K. 1993 Some reflections on solid state convection in the mantles of the Earth, Moon and terrestrial planets. In *Flow and creep in the solar system: observations, modeling and theory* (ed. D. B. Stone & S. K. Runcorn), pp. 67–82. Kluwer.

Runcorn, S. K. 1996 Preferred paths of VGPs in geomagnetic reversal records and their significance. In *Special issue about reversals of the Earth's magnetic field* (ed. E. Herrero-Bervera). *Surv. Geophys.* **17**, 229–232.

Ruocco, M. 1991 Sequential reversals from the Southern Hemisphere. *Geophys. Astrophys. Fluid Dynam.* **60**, 141–148.

Shackleton, N. J., Berger, A. & Peltier, W. R. 1990 An alternative astronomical calibration of the lower Pleistocene time scale based on ODP Site 677. *Trans. R. Soc. Edinb.* **81**, 251–261.

Steinhauser, P. & Vincenz, S. A. 1973 Equatorial paleopoles and behavior of the dipole field during polarity transitions. *Earth Planet. Sci. Lett.* **19**, 113.

Stephenson, F. R. & Morrison, L. V. 1984 Long-term changes in the rotation of the Earth: 700 BC to AD 1980. *Phil. Trans. R. Soc. Lond.* A **313**, 47–70.

Theyer, F., Herrero-Bervera, E., Hsu, V. & Hammond, S. R. 1985 The zonal harmonic model of polarity transitions: a test using successive reversals. *J. Geophys. Res* **90**, 1963–1982.

Tric, E., Laj, C., Jehanno, C., Valet, J.-P., Kissel, C., Mazaud, A. & Iaccarino, S. 1991*a* High-resolution record of the Upper Olduvai transition from Po Valley (Italy) sediments: support for dipolar transition geometry? *Phys. Earth Planet. Int* **65**, 319–336.

Tric, E., Laj, C., Valet, J.-P.,Tucholka, P., Paterne, M. & Guichard, F. 1991*b* The Blake geomagnetic event: transition geometry, dynamical characteristics and geomagnetic significance. *Earth Planet. Sci. Lett* **102**, 1–13.

Tauxe, L. 1993 Sedimentary records of relative paleointensity of the geomagnetic field: theory and practice. *Rev. Geophys.* **31**, 319–354.

Valet, J. P., Laj, C. & Langereis, C. 1988 Sequential geomagnetic reversals recorded in Upper Tortonian Marine Clays in Western Crete (Greece). *J. Geophys. Res.* **93**, 1131–1151.

Van Hoof, A. A. M. & Langereis, C. G. 1991 Reversal records in marine marls and delayed acquisition of remanent magnetization. *Nature* **351**, 223–225.

Weeks, R. J., Fuller, M. & Williams, I. 1988 The effects of recording medium upon reversal records. *Geophys. Res. Lett.* **15**, 1255–1258.

Weeks, R. J., Fuller, M., Laj, C., Mazaud, A. & Herrero-Bervera, E. 1992 Sedimentary records of reversal transitions-magnetization smoothing artefact or geomagnetic field behaviour? *Geophys. Res. Lett.* **19**, 2007–2010.

Williams, I. & Fuller, M. 1981 Zonal harmonic models of reversal transition records. *J. Geophys. Res* **86**, 11 657–11 665.

Received 10 August 1995; accepted 8 August 1996

MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES
THE ROYAL SOCIETY A
PHILOSOPHICAL TRANSACTIONS OF