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Polarity transitions and excursions of the geomagnetic field

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Introduction

The nature of geomagnetic field behavior during polarity transitions is one of the most hotly debated issues in modern geophysics. Dynamo action in the earth's fluid outer core is known to be responsible for generating the earth's main magnetic field, however, the mechanism for polarity transition is still unknown. Polarity transitions are a fundamentally important property of the geomagnetic field, but because they have not taken place in historic time, it is necessary to turn to the paleomagnetic record to understand the mechanism by which they occur.

Ever since the first detailed records of transitional geomagnetic field directions were obtained [e.g. *van Zijl et al.*, 1962], paleomagnetists have sought to understand the behavior of the field during polarity transitions. Early workers concluded that the transitional field was dominantly dipolar, based on the observation that virtual geomagnetic poles (VGPs) from polarity transitions recorded at different sites all tended to lie along the same path [*Creer and Ispir*, 1970; *Steinhauser and Vincenz*, 1973]. A direct test of the dipolar hypothesis was made by *Hillhouse and Cox* [1976] who compared their record of the Matuyama-Brunhes transition (780 kyr) at Lake Tecopa, California, with a record of the same reversal from the Boso Peninsula, Japan [*Niitsuma*, 1971]. The VGP paths determined from California and Japan did not overlap, and it was concluded that the geomagnetic field was not dominantly dipolar, but complex and predominantly non-dipolar, during the Matuyama-Brunhes polarity transition. As more records of a single reversal were obtained, it became evident that VGP paths were located close to the longitude of the site or antipodal to it, suggesting a transitional field that was roughly symmetrical about the earth's rotation axis [e.g. *Hoffman*, 1977; *Hoffman and Fuller*, 1978; *Fuller et al.*, 1979]. The common-site-longitude model was readily testable and many additional transitional records were obtained. This hypothesis adequately accounted for the field behavior observed in many records, however, a growing number of records provided evidence that the transitional fields were complex with significant non-axisymmetric components [e.g. *Herrero-Bervera and Theyer*, 1986; *Valet et al.*, 1988a; *Clement*, 1991; *Clement and Kent*, 1991]. *Tric et al.* [1991] compiled a large data set of records of different polarity transitions and short polarity events from sedimentary sequences that span the last 10 myr. They noted a visually compelling longitudinal confinement of transitional VGP paths of these records along a meridian over the Americas, and to a lesser extent, antipodal to it along a meridian over western Australia and east Asia. The records of *Clement* [1991] and *Clement and Kent* [1991] also suggest a confinement of VGP paths over the same pair of longitudes. This observation led *Tric et al.* [1991] and *Laj et al.* [1991] to suggest that dipolar field configurations may have dominated transitions over the last 10 myr.

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It therefore appears, as pointed out by *Bogue* [1991], that we have gone full circle, with the recent revival of dipolar transitional field hypotheses. The purpose of this paper is to selectively review developments during the last quadrennium concerning our knowledge of the behavior of the geomagnetic field during polarity transitions and excursions. An excellent description of many of the concepts discussed below is given by *Merrill and McFadden* [1990] and by *Jacobs* [1994]. Other recent reviews include those by *Clement and Constable* [1991], *Bogue and Merrill* [1992], *Gubbins* [1994], and *Jacobs* [1994]. The reviews by *Clement and Constable* [1991] and *Bogue and Merrill* [1992] predate many of the developments outlined here. The review by *Gubbins* [1994] deals mainly with connections between polarity reversals, historical records of secular variation, developments in dynamo theory and possible effects of core-mantle interactions on the geodynamo. *Jacobs* [1994] gives a detailed and up-to-date account of transitional field behavior, although many of the developments outlined here occurred subsequent to the completion of his book. The emphasis of the present paper is on the paleomagnetic record of polarity transitions and the vigorous debate that has surrounded recent analyses of transitional field behavior. Geomagnetic excursions are discussed insofar as they relate to the discussion concerning transitional field behavior.

Dominantly Dipolar Transitional Field Geometries?

Laj et al. [1991] contend, based on the observations of *Clement* [1991] and *Tric et al.* [1991], that a preponderance of transitional VGPs along the longitude of the Americas, and its antipode, from multiple records of the same polarity transition, as well as from records of different polarity transitions and geomagnetic excursions over at least 10 myr, may reflect inherent characteristics of the geodynamo. These "preferred" bands of longitude delineate zones which are also important in other geophysical observations, including: the boundaries of large non-dipole features of the present geomagnetic field (indicating strong flow of core fluid), as identified by *Bloxham and Jackson* [1991], and regions of fast seismic wave propagation (and therefore low temperature) in the lower mantle [*Olson et al.,* 1990]. *Laj et al.* [1991] suggest that it is not coincidental that the longitudes of north-south core fluid flow are also preferred by transitional VGPs. The time constants of mantle convection are orders of magnitude longer than those of the core, therefore the inferred persistence of the pattern of VGP bands over periods of at least 10 myr suggests that fluid flow in the core and/or lateral variations in electrical conductivity at the core/mantle boundary are modulated by mantle convection. *Runcorn* [1992] has suggested that the D″ layer, a physically and chemically distinct, 200 km thick layer in the lowermost mantle, may hold the key to the preferred transitional VGP paths. *Runcorn* [1992] hypothesized that the inhomogeneous D″ layer has a near metallic conductivity below the Pacific hemisphere which screens the secular variation generated in the earth's core, giving rise to the well known Pacific non-dipole low. In the hypothesis of *Runcorn* [1992], the conducting hemispherical shell would interact with a reversing dipole in the core to produce an electromagnetic torque that rotates the core so that the reversing dipole path lies along the boundaries of the shell, i.e., along longitudes including the Americas and Australia–east Asia.

Hoffman [1991] presented results from several volcanic records of Pliocene and Pleistocene polarity transitions from the Hawaiian and Society Island hotspots. The intermediate VGPs from all of these records cluster in geographically restricted regions which coincide with the bands of longitude identified in sedimentary records by *Laj et al.* [1991]. Because the clusters occur in separate volcanic records of polarity transitions that vary in age over the last several million years, *Hoffman* [1991] suggests that particular field configurations may dominate much of the reversal process and that several long-lived field configurations may recur during successive polarity reversals. The observation of longitudinal confinement of VGPs in sedimentary records of polarity transitions may, according to *Hoffman* [1991], reflect a directional bias imposed by smoothing during remanence acquisition [*Rochette,* 1990] of long-lived transitional field orientations, rather than a continuous dominantly dipolar transition process.

Valet et al. [1992] made a statistical analysis of a similar data set as that used by *Tric et al.* [1991] to test the significance of the visual indication of a concentration of transitional paths over preferred longitudes, as suggested by *Laj et al.* [1991]. Using a χ^2 test on a parameter which they refer to as the MVL (mean value of longitude), *Valet et al.* [1992] divided the earth into 18 sectors, each with a 20° width in longitude, and found that there was no reason to reject the hypothesis of a uniform distribution of transitional paths. *Valet et al.* [1992] concluded that their analysis is incompatible with a dominantly dipolar transitional field. In addition to this analysis, *Langereis et al.* [1992] presented evidence further to that of *Rochette* [1990] which suggests that the hypothesized longitudinal confinement of VGPs can arise from the smoothing of non-antipodal stable directions that occur just before and just after a geomagnetic reversal because of filtering during sedimentary remanence acquisition. Based on extensive studies of numerous reversal records from Crete [*Valet et al.,* 1988a], Sicily [*van Hoof and Langereis,* 1991, 1992a,b], and Calabria [*Linssen,* 1991], *Langereis et al.* [1992] suggest that there is reason for considerable caution in interpreting paleomagnetic records from relatively slowly deposited sediments. Their analysis of these central Mediterranean records reveals that non-transitional directions from zones of full reversed and normal polarity, as well as near-transitional directions immediately above and below the transitions, are significantly non-antipodal for most of the records examined (i.e. they fail to pass the reversal test). *Langereis et al.* [1992] modelled the transitional data by constructing a VGP path for each reversal which was obtained by filtering the non-transitional mean directions of the under- or overlying polarity zones. The modelled paths were then compared with the observed paths and it was found that 80% of the records are successfully modelled by smoothing of non-antipodal directions. The validity of the Mediterranean sequences as reliable recorders of transitional field behavior must therefore be questioned. This is particularly the case when authigenic, biogenic and diagenetic processes, including cyclically fluctuating paleoredox conditions, give rise to more than one remanence-bearing mineral with remanences that are locked in at different depths, as demonstrated by *van Hoof and Langereis* [1991, 1992a,b]. *Roberts and Turner* [1993] also point out that caution should be exercised in interpreting polarity transition records from sediments in which ferrimagnetic iron sulfide minerals have formed, because of possible lags in timing of remanence acquisition between different magnetic phases.

Regardless of the uncertainty concerning the Mediterranean records, many sediments are capable of providing high-resolution records of transitional field behavior. *Clement and Martinson* [1992] obtained replicate records of transitional field behavior from the Cobb Mountain polarity interval (1.2 myr) from two North Atlantic deep-sea cores which are separated by approximately 1300 km. The degree of similarity in the serial correlation of features in the two records demonstrates that they are not artifacts of remanence acquisition processes. The VGP paths of these records are indistinguishable from the path obtained from what is inferred to be a record of the Cobb Mountain polarity interval in lavas from Tahiti [*Chauvin et al.,* 1990]. *Clement* [1992] augmented this comparison with two other records of the Cobb Mountain polarity interval from deep-sea cores in the western Pacific (Celebes and Sulu Seas). All of the records discussed by *Clement and Martinson* [1992] and *Clement* [1992] have strikingly similar transitional VGP paths which tend to fall along antipodal meridians, providing evidence of a dominantly dipolar transitional field during the Cobb Mountain reversals. However, the tracks of these paths are centered over Africa and the central Pacific, rather than the bands noted by *Laj et al.* [1991]. Because the Cobb Mountain polarity interval and the reversals discussed by *Laj et al.* [1991] occurred over time intervals too short for significant changes to have occurred in the lower mantle, the differences in these transitional fields are difficult to reconcile with the hypothesis of lower mantle control on the geodynamo. It should also be noted that *Abrahamsen and Sager* [1994] have recently published three records of the Cobb Mountain polarity transitions from the Lau Basin which conflict with the simple transitional field geometries suggested by *Clement and Martinson* [1992] and *Clement* [1992].

The hypothesis of preferred transitional VGP paths also received support from a study of secular variation from lava flows that span the last 5 myr, in which *Constable* [1992] reported a bias in the longitudes of the VGPs of the stable field. The preferred longitudes reported from the secular variation data are identical to those reported from the polarity transition data [*Clement,* 1991; *Laj et al.,* 1991]. *Constable* [1992] suggested that the preferred longitudes observed in the polarity transition data may be explained if the axial dipole part of the modern geomagnetic field decayed and grew back with opposite polarity, while the modern non-axial dipole component remained the same. However, *Quidelleur et al.* [1994] and *Johnson and Constable* [in press] have performed further analyses of secular variation from lavas with data bases that differ significantly from that used by *Constable* [1992] and both sets of authors find a much more homogeneous VGP longitude distribution than that reported by *Constable* [1992]. *Johnson and Constable* [in press] claim that the main conclusion of *Constable* [1992] still holds. That is, there exists evidence for non-zonal structure in the time-averaged paleofield [e.g. *Gubbins and Kelly,* 1993], however, there is no obvious link between secular variation VGP longitude distributions and the preferred VGP longitude bands observed in some polarity transition records [*Clement,* 1991; *Tric et al.,* 1991; *Laj et al.,* 1991].

The contention by *Laj et al.* [1991] that transitional VGPs follow "preferred" paths has been the subject of ongoing debate. In a response to *Valet et al.* [1992], *Laj et al.* [1992a] argue that the χ^2 test is unreliable with such a small set of available polarity transition records. Instead, *Laj et al.* [1992b] followed up their response to *Valet et al.* [1992] with a statistical analysis of the equatorial crossings of reversal paths based on three standard tests used in circular statistics. These tests are more suitable than a χ^2 test because they do not require any a priori partitioning of the data into longitudinal bins and they allow discrimination of whether a non-random distribution is unimodal or bimodal. *Laj et al.* [1992b] conclude that their statistical tests support the visual impression of a preponderance of transitional VGP paths over the Americas and, to a lesser extent, its antipode. In a companion paper, *Weeks et al.* [1992] addressed the challenge by *Langereis et al.* [1992] that sedimentary records of reversal transitions reflect artifacts of remanence smoothing. *Weeks et al.* [1992] modelled hypothetical polarity transition data to show that smoothing over unrealistically long time scales is required to generate intermediate directions that are purely mixtures of pre- and post-transitional directions for sediments in which the remanence is primarily depositional or post-depositional in nature. Therefore, if single remanence components are isolated during stepwise demagnetization, preferential longitudes of transitional VGP paths will be due to field behavior rather than an artifact of the magnetization process. If mixtures of primary and secondary magnetizations occur and cannot be separated, then artifacts can be generated. Therefore, as would be agreed by all workers, the demonstration of the fidelity of a particular record is clearly a key aspect of modern polarity transition studies. As a result of their analyses, *Laj et al.* [1992b] and *Weeks et al.* [1992] claim that, based on the presently available data, a physical explanation should be sought for the apparent longitudinal bias in the transitional VGP distribution.

Further support for dipolar transitional field behavior and for mantle control of the orientation of reversing fields come from two southern hemisphere and two northern hemipshere clusters of directions from volcanic records presented by *Hoffman* [1992]. Interpretation of polarity transition records from lavas is complicated by the lack of knowledge of eruption frequency. A few eruptions over a period of a few weeks or months could give rise to a cluster of directions that has no relevance to long-lived transitional field states. However, *Hoffman's* [1992] data are from ten late Cenozoic records from five widely separated sites around the world. *Hoffman* [1992] therefore claims that this distribution provides strong support not only for the contention that the reversal process is dominated by long-lived and recurring transitional field states, but also that the VGP clusters are associated with standing transitional orientations. Notwithstanding the problem of smoothing during remanence acquisition in sediments, these volcanic data provide strong corroboration of the sedimentary data. Furthermore, the positions of these VGP clusters coincide closely with regions of fast seismic P-wave propagation in the lower mantle [*Dziewonski and Woodhouse,* 1987] and localities of flux expulsion of the geomagnetic field at the core-mantle boundary [*Gubbins and Bloxham,* 1987]. These associations led *Hoffman* [1992] to suggest that the hypothesized recurring inclined dipolar states during field reversals arise from localized longstanding thermodynamic features of the core-mantle system. *Brown et al.* [1994] subsequently published a southern hemisphere volcanic record of the Matuyama-Brunhes transition from the Chilean Andes which supports *Hoffman's* [1992] suggestion of VGP clusters and dominantly dipolar transitional field geometries.

A striking resemblance is also seen in the concentrations of flux at the core-mantle boundary between a global set of paleomagnetic data, spanning the last 2.5 myr, and the modern geomagnetic field [*Gubbins* *and Kelly*, 1993]. These authors therefore propose that the present geomagnetic field morphology and pattern of secular variation have persisted for several million years. This finding implies mantle control of the flow in the top of the core and, if such concentrations of flux persist during polarity reversal, the concentrations could dictate the position of transitional VGPs, thus providing further support for the hypothesis of *Laj et al.* [1991]. However, *Gubbins and Coe* [1993] note that while there is evidence for longitudinal bias of transitional VGP paths and an underlying mantle control of flow in the outer core, confined VGP paths are not necessarily evidence of near-dipolar transitional fields. *Gubbins and Coe* [1993] present a simple model in which confined VGP paths arise despite a substantially non-dipolar structure of the transitional field.

The controversy concerning transitional field behavior has not subsided. *McFadden et al.* [1993] performed yet another statistical analysis of the transitional field data base, motivated by the observations that none of the previous tests have a hypothesis of preferred sectors as an alternative to the null hypothesis of uniform randomness and that the hypothesis of *Laj et al.* [1991] has yet to be tested specifically. The test devised by *McFadden et al.* [1993] uses a disk with the MVL or equatorial crossing values placed around its circumference. A rotator, with lobes described by an angle, θ, denoting the width of the longitudinal band, is turned until it covers the maximum number of observed values. This observed value can then be compared with a test statistic that is observed from a uniform random distribution around the equator. Also, one or two lobes may be used on the rotator to test for unimodality or bimodality. The results of this test show an overall preference for the two antipodal bands of *Laj et al.* [1991]. However, by applying the same test to the longitudes of the sites from which polarity transition records have been obtained, it is evident that the site longitudes are more strongly grouped than the equatorial crossings of the transitional paths. *Egbert* [1992] has shown that the effect of the transformation used to calculate VGPs, in spherical coordinates on simple, statistically homogeneous paleomagnetic directions, will produce a distribution of longitudes that is peaked $\pm 90°$ from the longitude of the sampling site. Unless the sampling sites are uniformly distributed, the VGP longitudes would not be expected to be uniformly distributed. It is therefore possible that the longitudinal confinement of VGP paths may be a statistical artifact resulting from the distortion of the VGP transformation and the non-uniformity of sampling sites. While it is not clear that this type of bias can explain the preferred VGP paths, the possibility of bias should be considered before accepting the hypothesis of mantle control of the reversal process. Therefore one must conclude that, with the present data base, it is premature to accept the hypothesis of *Laj et al.* [1991]. However, this model is readily testable and future efforts should concentrate on obtaining high quality records from a broader distribution of sampling longitudes.

The sedimentary polarity transition data sets used in the compilations by *Tric et al.* [1991], *Laj et al.* [1991, 1992b], and *McFadden et al.* [1993] comprised a combination of records from polarity reversals and geomagnetic excursions, while the data set used in the statistical analysis of *Valet et al.* [1992] was strictly confined to records of polarity reversals. *Quidelleur and Valet* [1994] made a further statistical analysis, using the rotator test of *McFadden et al.* [1993], of the MVLs of a joint data set that includes both records of geomagnetic excursions and polarity reversals, as well as separate analyses of the two different types of records. Different characteristics emerge from the two analyses: the VGP paths from excursions do not cluster about any preferred longitude, while the polarity reversal records that have low dispersions of the MVL are preferentially grouped in a longitudinal sector over the Americas and its antipode. However, because of the non-uniform site distribution, most of the MVLs are $\pm 90°$ from their site longitudes. Based on the premise that excursions and polarity reversals are similar phenomena, and that they should therefore show similar distributions of transitional VGP paths, *Quidelleur and Valet* [1994] revive the suggestion that the two preferred sectors of longitude result from sedimentary artifacts due to remanence acquisition processes.

Zhu et al. [1994a] studied the Matuyama-Brunhes and upper Jaramillo polarity transitions in a loess sequence in central China. Both records have longitudinally-confined transitional VGP paths that lie along the two preferential sectors previously noted from marine and continental records [*Clement*, 1991; *Laj et al.*, 1991]. The location of the sampling sites extends the geographical distribution of sites in the data bases used to assess systematics in transitional field behavior and *Zhu et al.* [1994a] have performed another statistical analysis which employs the rotator test of *McFadden et al.* [1993], but which is restricted to records of polarity transitions, with excursion records being omitted. *Zhu et al.* [1994a] obtained similar results to those of *Quidelleur and Valet* [1994] which suggest that the largest contribution to the scatter in the longitudinal distribution in previous analyses is due to the inclusion of geomagnetic excursion records. *Zhu et al.* [1994a] also observe a longitudinal concentration of transition paths along the two preferential sectors when the polarity transition records are considered, however, unlike *Quidelleur and Valet* [1994], they conclude that there is a difference in the physical processes that dominate geomagnetic excursions and polarity transitions.

In response to the evidence presented by *Hoffman* [1992] for persistent inclined dipolar states during transitions, *Prévot and Camps* [1993] compiled approximately 400 intermediate poles from 121 volcanic records of excursions and polarity transitions less than 16 myr in age. They argue that the hypothesis of *Hoffman* [1992] is based on a set of selected transitional directions and that a wider analysis is necessary to test his hypothesis. Because several eruptions can occur over periods of weeks or months, *Prévot and Camps* [1993] explicitly preclude the possibility of single records showing long-standing features by excluding consecutive lava flows whose α_{95} confidence angles overlap. Using circular statistics on their large data set, *Prévot and Camps* [1993] conclude that there is no evidence of long-lived recurrent inclined dipolar states. The evident discrepancy between their analysis of volcanic records and the sedimentary records leads these authors to again suggest a critical re-evaluation of the magnetization acquisition process.

If the continued assault on the reliability of sedimentary records of polarity transitions was not sufficiently disconcerting, re-examination of the Lake Tecopa, California, site has yielded yet another interpretation of the well known Lake Tecopa record. This site was first investigated by *Hillhouse and Cox* [1976] who showed that the transitional VGP path yielded a different record from that of the Boso Pensinsula in Japan [*Niitsuma*, 1971] (It should be noted that the Boso Peninsula record of *Niitsuma* [1971] has recently been superceded by the work of *Okada and Niitsuma* [1989]). *Valet et al.* [1988b] reinvestigated the Matuyama-Brunhes transition near the locality of *Hillhouse and Cox* [1976], using both alternating field (AF) and thermal methods, and found a transitional interval of intermediate remanence directions and mixed polarities that differed substantially from that of the previous study in which only AF methods were used. *Larson and Patterson* [1993] carried out another reinvestigation of the Lake Tecopa record at three sites and found that the zones of intermediate directions differ greatly in polarity character, thickness, and stratigraphic position. They conclude that the mutually contradictory records provide evidence that none of the records are acceptable for establishing the nature of the transition at Lake Tecopa. *Larson and Patterson* [1993] present evidence that the obliteration of the transition may be due to sedimentary diagenesis, including zeolite alteration, as has been documented in the Tecopa Basin by *Verosub and Summa* [1993]. This study reinforces the importance of not only considering the effects of directional smoothing due to remanence acquisition processes [*Rochette,* 1990; *Langereis et al.*, 1992; *Weeks et al.*, 1992], but also the effects of diagenesis on the paleomagnetic record [cf. *van Hoof and Langereis*, 1991, 1992a,b; *Roberts and Turner*, 1993].

Glen et al. [1994] made a detailed re-examination of a record of the Gauss-Matuyama transition from Searles Valley, California, which they claim is not hampered by problems due to smoothing or recording breakdown. This transition record is longitudinally unconfined which suggests that the reversing field has either a wider spectrum of behavior than has been proposed in recent years or that the field is dominated by complicated geometries during transition. *Glen et al.* [1994] compare their record with other records (both volcanic and sedimentary) from the same geographic region and identify a common swath of VGPs that stretch from west Africa to the southwest Pacific, with a notable absence of VGPs over a large area centered on the Indian Ocean. Because this apparently persistent feature of transition records from western North America is offset from the features seen in global compilations, *Glen et al.* [1994] suggest that the persistent fields have a non-dipolar component. Clearly, much more work is needed to clarify the current divergence of opinion concerning the nature of the transitional geomagnetic field.

Polarity Transitions and Excursions

In the last decade, there have been many reports of geomagnetic excursions, in which VGPs deviate more than 40 or 45° from the axial geocentric dipole field direction. It has become popular to think of excursions as aborted reversals because of the short-lived, but large, swing in VGP towards values of opposite polarity. Some authors refer to Brunhes Chron (0–780 kyr) excursions as subchrons (a subchron is a zone bounding two closely spaced polarity transitions; e.g. *Spell and McDougall* [1992] accept eight subchrons during Brunhes time). If such zones are real subchrons, they have important implications for geomagnetic field behavior because they imply that the reverse polarity state has been less stable than the normal polarity state for the past 780 kyr. Publication of a substantially new geomagnetic polarity timescale for the late Cretaceous and Cenozoic by *Cande and Kent* [1992] provided *Merrill and McFadden* [1994] with the opportunity to re-examine the relative stabilities of the normal and reverse polarity states. Their analysis confirms the previous conclusions of *McFadden et al.* [1987] that there is no reason to reject the hypothesis of a common stability for the normal and reverse polarity states at any time during the Cenozoic. Given this confirmation, *Merrill and McFadden* [1994] conclude that it is necessary to question the reality of the numerous claims of short reverse polarity subchrons in the Brunhes chron. After examining the literature, they conclude that there is no convincing evidence for reversed subchrons in the Brunhes chron and that the only sufficiently well documented geomagnetic excursions are the Laschamp and the Blake excursions. Many authors make no distinction between excursions and aborted reversals [e.g. *Tric et al.*, 1991; *Hoffman*, 1992; Quidelleur and Valet, 1994] and excursion records are commonly included in statistical analyses of transitional field behavior. *Merrill and McFadden* [1994] consider the evidence for excursions as aborted reversals as equivocal. For example, the Laschamp and Blake excursions appear to occur when the non-dipole to dipole field ratio was large with a low dipole field intensity, without evidence for reversal of the dipole. As a consequence of the possible difference in causal mechanism for polarity reversals and excursions, *Merrill and McFadden* [1994] advocate that polarity transitions and excursions should be treated separately when the data sets are examined to determine if systematics are present.

The Pringle Falls (Oregon) record of *Herrero-Bervera et al.* [1989] has been widely cited as the most detailed record of the Blake excursion. *Herrero-Bervera and Helsley* [1993] have confirmed the earlier Pringle Falls study by obtaining a second record from another sedimentary sequence, 1.5 km away from the original site, which duplicates all of the features seen previously. *Herrero-Bervera and Helsley* [1993] and *Zhu et al.* [1994b], who describe a record of the Blake excursion from a Chinese loess sequence, suggest that the common features observed in numerous records support the global nature of the Blake excursion. *Herrero-Bervera et al.* [1994] and *Negrini et al.* [1994] have demonstrated, on the basis of correlation of paleomagnetic directions, tephrochronology, and radiometric dating, that the Pringle Falls record is synchronous with excursion records from Summer Lake (Oregon) and Long Valley, California. These records represent a distinct and synchronous geomagnetic excursion, with concomitant low field intensities [*Roberts et al.,* 1994], which must be considered one of the best documented multiple records of a single excursion. However, $^{40}Ar/^{39}Ar$ dating of a tephra layer that is closely associated with the excursion at all three western North American localities, demonstrates that the excursion is considerably older than the inferred age of the Blake excursion [*Herrero-Bervera et al.,* 1994; *Negrini et al.,* 1994]. Clearly, this finding has important implications for the inferred global nature of the Blake excursion.

Field Intensities During Polarity Transitions and Excursions

In her review of sedimentary records of relative paleointensity, *Tauxe* [1993] briefly discussed seven relative paleointensity records of the Matuyama-Brunhes transition. *Tauxe* [1993] notes broad similarities between the records in that the transition zones are associated with low relative paleointensities. *Valet and Meynadier* [1993] then produced the first detailed relative paleointensity record that continuously spans the last 4 myr and which crosses numerous polarity reversal boundaries. The most significant feature of this record is the gradual decrease in field intensity prior to most polarity transitions and the rapid rise to high intensity after each transition. This picture has been confirmed by duplicate records, from three ocean basins, that cross the Matuyama-Brunhes transition [*Valet et al.,* 1994], as well as from the lower and upper Jaramillo and Matuyama-Brunhes transitions from the central North Pacific Ocean [*Verosub et al.,* ms]. *Bogue and Paul* [1993] obtained absolute paleointensity data from a sequence of Hawaiian lava flows which were erupted immediately following a geomagnetic reversal. They note that field intensities were low during the transition and unusually high in the interval immediately following the reversal, similar to the behavior observed in the Steens Mountain (Oregon) volcanic sequence [*Prévot et al.,* 1985]. A coherent picture therefore seems to be emerging that indicates that field intensities decay during a polarity chron, culminating in low values during the polarity transition, followed by a rebound to high intensities in the interval immediately after the transition. Nevertheless, the details of this asymmetrical saw-tooth paleointensity pattern of *Valet and Meynadier* [1993] will remain the subject of debate until such behavior is more widely observed.

These studies demonstrate the importance of obtaining the paleointensity which is usually the missing third component of paleomagnetic studies. *Mary and Courtillot* [1993] have stressed the importance of this component because it allows a full three-dimensional (3D) representation of geomagnetic polarity transition records. *Mary and Courtillot* [1993] present 3D polarity transition data in local cartesian coordinates (analogous to vector component or "Zijderveld" projections) which allows the examination of polarity transition records for systematic behavior. *Lin et al.* [1994] analysed four of the best known volcanic polarity transition records and one excursion record from which high quality absolute paleointensity data are available. They found a significant correlation between the virtual dipole moment and the angle between the VGP and the earth's rotation axis. This result suggests that physical models for geomagnetic field behavior must address the question of how changes in direction are linked to changes in intensity during polarity transitions.

Oppenheim et al. [1994] obtained transitional field directions from a series of lower Carboniferous lavas which yield paleointensity estimates that lie between 10 and 20% of other estimates of the lower Carboniferous field intensity. This suggests that Paleozoic geomagnetic polarity reversals were similar to more recent polarity transitions in that they involve a major decline in field intensity. Low field intensities are also associated with low latitude VGPs from the Summer Lake excursion record in Pleistocene sediments [*Roberts et al.,* 1994] and an excursion from volcanic rocks in Germany [*Schnepp and Hradetsky,* 1994]. The directional signature of the Summer Lake excursion [*Negrini et al.,* 1994] is attenuated with respect to the other records of the same excursion [cf. *Herrero-Bervera and Helsley,* 1993]. *Negrini et al.* [1994] postulate that this may be due to overprinting by the subsequent high-intensity field, as has been proposed by *Coe and Liddicoat* [1994] for the most detailed record of the Mono Lake excursion in the Mono Lake Basin of California [*Liddicoat,* 1992]. Alternatively, the directional attenuation may result from sedimentary smoothing due to the relatively low sedimentation rate at Summer Lake with respect to Pringle Falls.

Discussion

This review clearly demonstrates that there is currently a considerable divergence of opinion concerning the nature of the transitional geomagnetic field and the status of geomagnetic excursions. Further work needs to be undertaken not only to obtain a large number of high quality records, but also to come to a better understanding of the mechanisms that give rise to remanence acquisition in sediments and the processes that act to compromise the fidelity of sedimentary records. A greater spatial distribution of sampling sites is needed, particularly more sites from the southern hemisphere. In terms of obtaining further records to test reversal models, three potential alternatives are evident [*Clement and Constable,* written comm., 1993].

Large-scale efforts need to be made to: 1) obtain as many records as possible of the Matuyama-Brunhes transition to map the field configuration during that polarity transition; 2) obtain as many records as possible from multiple reversals, with records of sequential polarity transitions from a site wherever possible, and 3) study a limited number of transitions in as many places as possible. The latter two options would yield the most information for testing for persistent features that may be associated with transitional fields. Further criteria should be added, such as recovering "normal" field behavior for about 25 kyr before and after each transition, and records with accumulation rates > 5 cm/kyr should be targetted. There is, of course, a trade-off between high temporal resolution and the effects of reductive diagenesis which are usually significant in rapidly deposited sediments.

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