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Deciphering records of geomagnetic reversals

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Key Points:
- We examine and assess an updated database of geomagnetic reversal records
- We discuss robust and controversial features of the transitional field
- Future work should involve millimeter-size specimens and physics-based models

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Abstract Polarity reversals of the geomagnetic field are a major feature of the Earth's dynamo. Questions remain regarding the dynamical processes that give rise to reversals and the properties of the geomagnetic field during a polarity transition. A large number of paleomagnetic reversal records have been acquired during the past 50 years in order to better constrain the structure and geometry of the transitional field. In addition, over the past two decades, numerical dynamo simulations have also provided insights into the reversal mechanism. Yet despite the large paleomagnetic database, controversial interpretations of records of the transitional field persist; they result from two characteristics inherent to all reversals, both of which are detrimental to an ambiguous analysis. On the one hand, the reversal process is rapid and requires adequate temporal resolution. On the other hand, weak field intensities during a reversal can affect the fidelity of magnetic recording in sedimentary records. This paper is aimed at reviewing critically the main reversal features derived from paleomagnetic records and at analyzing some of these features in light of numerical simulations. We discuss in detail the fidelity of the signal extracted from paleomagnetic records and pay special attention to their resolution with respect to the timing and mechanisms involved in the magnetization process. Records from marine sediments dominate the database. They give rise to transitional field models that often lead to overinterpret the data. Consequently, we attempt to separate robust results (and their subsequent interpretations) from those that do not stand on a strong observational footing. Finally, we discuss new avenues that should favor progress to better characterize and understand transitional field behavior.

1. Introduction

Geomagnetic reversals are an extreme manifestation of the variability of the geomagnetic field created and sustained by dynamo action in Earth's core. This variability spans a vast range of time scales, from days to millions of years. Composite power spectra of dipole fluctuations constructed from observations [*Constable and Johnson*, 2005] and numerical dynamo simulations [*Olson et al.*, 2012] point to an intermediate frequency band with periods from a few centuries to a few tens of kiloyears, where, according to *Olson et al.* [2012], the energy density increases with the period in an almost quadratic fashion; reversals (and excursions, i.e., failed attempts at reversal) lie within that transitional band (that of paleosecular variation). No obvious separation of excursional to reversing behavior exists, and the question remains whether reversals reflect core processes that are different from those at work behind regular paleosecular variation. In this review, our primary goal is to outline the constraints that current (and future) observations may help to place on these processes, by means of a detailed description of the so-called transitional field, i.e., the global geomagnetic field one would map out during a reversal. Good knowledge of transitional field behavior is also key to predicting how the Earth system (and, in particular, the magnetosphere) would evolve in the event of a reversal (see, e. g., the discussion by *Constable and Korte* [2006] and the review by *Glassmeier and Vogt* [2010]).

The first records of geomagnetic reversals were published more than 50 years ago [*Van Zijl et al.*, 1962; *Momose,* 1963]. Since then an increasing number of records have been obtained from rock types with diverse physicochemical processes of formation and magnetization. Most studies have dealt with sediments, no more than two dozens from lava flows, and three records from intrusions [*Dodson et al.,* 1978]. In most cases, identification of reversals relies on detailed magnetostratigraphic profiles for sediments and on radiometric ages for lava flows. Considerable progress has been achieved over the past 20 years by tuning carbonate variation in sedimentary sequences to Earth's orbital variations with a precision better than 20 kyr [*Imbrie et al.,* 1992]. However, this time span exceeds the duration of reversals. It is, therefore, difficult to determine rapid geomagnetic variations with adequate temporal precision. These differences are amplified by weak transitional fields that contribute to increase recording complexities.

Like any scientific topic, our knowledge about field reversals has been acquired through several steps. A first important objective was to determine whether the field would maintain a dipolar character when reversing. Early studies [*Creer and Ispir,* 1970] proposed that the field had retained dipolar configurations during seven polarity reversals recorded at widely separated sites. The motion of the pole through the Indian Ocean was simulated by a model of three dipoles that was rapidly discarded with accumulation of new results, mostly from sediments. The dipolar nature of the transition was also questioned by the first measurements of absolute paleointensity which showed that polarity changes are accompanied systematically by low field values [*van Zijl et al.,* 1962; *Momose,* 1963; *Coe,* 1967; *Lawley,* 1970; *Larson et al.,* 1971; *Niitsuma,* 1971; *Dagley and Wilson,* 1971]. These observations were reinforced by the dominance of low magnetization intensities associated with transitional lava flows [*Kristjansson and McDougall,* 1982]. The first compilation of volcanic records led *Dagley and Lawley* [1974] to favor a nondipolar transitional field. By then a succession of models had been proposed and tested against an increasing number of paleomagnetic data.

Knowledge of field geometry during polarity reversals remains limited due to the difficulty of acquiring well-documented records of the same transition from widely distributed locations, particularly from the Southern Hemisphere which remains relatively depleted of data. Despite advances in determining successive field directions, along with relative and absolute paleointensity changes during transitions, interpretations are hampered frequently by relatively poor knowledge of the processes involved in magnetization acquisition, especially for sediments, and by the absence of a detailed chronology for lava flow sequences.

The last reversal (Matuyama-Brunhes, M-B) has been the focus of much attention, because this is the first major event that can be recognized in marine sediment cores. The successive positions of the virtual geomagnetic pole (VGP)—the apparent location of the pole assuming an axial geocentric dipole field—that define the VGP path have been commonly used to infer features of the transitional field. The first five published M-B records showed some tendency of VGP paths to lie near the longitude of their sampling site. *Hoffman and Fuller* [1978] concluded that the transitional field was predominantly controlled by degree 2 or 3 zonal harmonics and, therefore, it was axisymmetric but not dipolar. As more detailed records of the last reversal and other events became available, these models could not be defended any more. It was then considered that the field was neither axisymmetric [*Hoffman,* 1979; *Fuller et al.,* 1979; *Valet et al.,* 1988a; *Prévot,* 1977; *Prévot et al.,* 1985; *Clement and Kent,* 1984] nor dipolar but likely controlled by nonzonal harmonics of low degree [*Hoffman,* 1984]. Unfortunately, in this case a large distribution of sites that record the same reversal is needed to determine the exact nature of the harmonic content. Studies of geomagnetic reversals turned toward a different prospect in the early 1990s with the aim of investigating the imprint of the lower mantle on the geomagnetic field [*Gubbins*, 1994].

Most inferences about the reversing field are controversial. We attempt to approach these topics from a different angle than previous reviews on reversals [*Clement and Constable*, 1991; *Bogue and Merrill*, 1992; *Jacobs,* 1994; *Roberts*, 1995; *Merrill and McFadden*, 1999; *Constable*, 2003; *Valet and Herrero-Bervera*, 2007; *Amit et al.,* 2010] and present here a critical review on the subject. We discuss the resolution and precision that can be expected to describe the transitional field. Many observations remain controversial due to limited constraints on magnetization signals and their temporal sampling. Using the last reversal as a detailed case study and evaluating the published database, we conclude that attempts at describing the first terms of the harmonic content of the transitional field remain premature. Another issue concerns the longitudinal preference of VGP paths during different reversals and/or the presence of VGP clusters that could reflect heterogeneous heat flux at the core-mantle boundary, but they could also be generated by rock magnetic or sampling artifacts. Finally, the magnetic field is a vector and studies of paleointensity are essential to document the transitional field. Few volcanic records provide successful paleointensity determinations, but those that do contain some coherent features. Dipole field intensity evolutions across various reversals from sedimentary records reveal interesting but controversial features. We finally report on promising avenues opened by new and supplementary techniques.

Parallel to data acquisition, activity has been invested in developing numerical dynamo models and analyzing their output (see the recent short review by *Glatzmaier and Coe* [2015]). We can now attempt to gain additional insights into reversal features revealed by paleomagnetic records with respect to those produced by numerical simulations.

2. Resolution of Paleomagnetic Records

In order to assess the role played by nondipolar components during transitions, we need to consider typical characteristic times of the recent nondipole field, of which we have an arguably reasonable knowledge. The characteristic time scales of secular variation can be estimated from spatial power spectra of the main field and of its secular variation. These time scales represent statistically the time it would take for the energy of the field at spherical harmonic degree n to be completely renewed [*Hulot and Le Mouël,* 1994]. The time scales of the nondipole field ($n > 1$) are compatible with an inverse linear law of the form $\tau_n = \tau_{sv}/n$ with a master coefficient, the secular variation constant τ_{sv}, of the order of 500 years [*Lhuillier et al.,* 2011a], when estimated based on the historical geomagnetic field model *gufm1* [*Jackson et al.,* 2000]. Therefore, over a period of approximately 1 kyr, the nondipole field will be reorganized substantially. In addition, τ_n values for low n, which can be computed directly using time-averaged spectra of the field and secular variation of the regularized holocene field model CALS10k.1b [*Korte et al.,* 2011] range from 458 years ($n = 2$) to 155 years ($n = 6$). We take from these figures that proper description of nondipole field evolution requires a temporal resolution that should be less than a millennium.

The concept of transitional directions does not have any clear theoretical meaning. It is convenient to consider that a direction is transitional when it exceeds the normal range of secular variation. However, if we assume that reversals belong to a continuum of geomagnetic changes covering the characteristic time scales for secular variation and excursions, this definition is not meaningful since directions pointing far away from the direction of the axial dipole field at the site can also be generated by secular variation in weak field. Transitional directions are usually defined from VGP latitudes that are either lower than 60° or 45° (60° is commonly used for volcanics while 45° is more often adopted for sediments where inclination shallowing is common). When a detailed record of paleosecular variation accompanies a reversal, it is convenient to refer to the maximum change in amplitude reached during the surrounding intervals of stable polarity. Another approach has been proposed by *Vandamme* [1994] that takes into account the limit of VGP scatter around the mean pole position. This technique requires good knowledge of the local field during periods of full polarity surrounding the transition. We must also be aware that the criteria used to define reversal boundaries rely on directions and not on the full vector. The local field direction is constrained by the axial dipole intensity and the remaining nonaxial dipole field (i.e., the field without the axial dipole, frequently referred to as the nonaxial dipole field, NAD). Depending on site location, a large axial dipole decrease may not always be accompanied by a significant deviation of the local field direction, despite being related to transitional processes. Therefore, in such cases paleointensity determinations are crucial.

2.1. The Convoluted Signal of Magnetic Remanence in Sediments

The continuous character of sediment records is attractive when studying short geomagnetic events like reversals, but this advantage is counterbalanced by their weak magnetization. For this reason, development of the first cryogenic magnetometers in the 1970s enabled accurate measurement of weakly magnetized sediment samples, which opened the way to studies of polarity transitions and secular variation. Typical 8 cm^3 single samples used for magnetic measurements average the field over the time required for deposition of 2 cm of sediment. This constraint alone makes it impossible to obtain clues about nondipole field changes recorded at deposition rates lower than 10 cm/kyr if one wishes to have a 200 year resolution. Smaller subsamples can be used, but we then have the delicate task of sampling thin slices of sediment without introducing disturbances, a problem that is amplified by the weak magnetization of transitional samples. Resolution becomes even poorer when analyzing long continuous sections of sediment (refered to as U-channels) since the wide response curves of the magnetometers (i.e., the sediment thickness integrated in each measurement) generate additional smoothing [*Nagy and Valet,* 1993; *Weeks et al.,* 1993]. Similar conclusions were reached for records of geomagnetic excursions by *Roberts and Winklhofer* [2004].

Further complexity arises from the magnetization process itself. There is strong evidence that bioturbation (i.e., mixing of sediment by biological activity) introduces an offset between the position of the actual reversal and its record within the sediment. Under such conditions, it is difficult to argue that magnetization lock-in occurs immediately below the bioturbated layer. There is an ongoing debate regarding the way sedimentary magnetization is acquired. Only a small portion of magnetic grains is oriented by the field. A key question is to determine whether this is caused by integration of magnetic grains within sedimentary flocs that impede their alignment with the field and if such aggregates form in the water column, at the sediment-water interface, or below the bioturbated layer [*Katari and Bloxham*, 2001; *Tauxe et al.*, 2006; *Shcherbakov and Sycheva,* 2010; *Spassov and Valet*, 2012; *Roberts et al.*, 2013]. The most stable part of the magnetization carried by fine particles is oriented during periods of full polarity, in the presence of stronger fields than during reversals. This raises the question of whether these grains can be oriented when the field is 1 order of magnitude weaker.

Magnetization lock-in is argued to result from a progressive decrease in sediment water content [*Irving and Major,* 1964; *Kent,* 1973]. We thus suspect that magnetization is acquired over at least a 10–15 cm deep interval [e.g., *Channell and Guyodo*, 2004; *Liu et al., 2008*; *Suganuma et al.*, 2011; *Ménabréaz et al.*, 2014]. Assuming a deposition rate of 6 cm/ka and a 12 cm deep interval for lock-in, the sediment magnetization will integrate field changes over a 2 kyr long period. Even with a 6 cm lock-in zone, the signal is smeared over a 1 kyr period, which is too long to properly document variations of nondipole field components.

2.2. Limits Imposed by Sediment Depositional Processes

The effect of deposition rate and lock-in depth on the resolution of sedimentary paleomagnetic records can be investigated by referring to the historical and archeological field. The most complete record of paleosecular variation for the past 5 ka has been obtained from the big island of Hawaii [*Hagstrum and Champion,* 1995]. Each unit has a ^{14}C age with an averaged uncertainty of 120 years. In parallel, a highly detailed sedimentary record has been obtained from nearby Lake Waiau from the summit of Mauna Kea [*Peng and King*, 1992]. This unique situation allows comparison of these two independent detailed and accurate data sets of field changes during the past 5 ka. The two inclination patterns in Figure 1a are similar, except for intervals that seem to be offset from each other likely because of dating inaccuracies. A striking observation is that all short-term fluctuations present in the lava record appear to be smoothed out in the sedimentary record. The variations present in the volcanic data do not result from errors in sample orientation or from tilting of lava flows. Their presence cannot be linked to the magnetization process and, therefore, reflect local geomagnetic changes. We have investigated the time window required to smear out the variations in order to reconcile the records. If we simulate a marine record characterized by the same deposition rate of 43 cm/kyr as at Lake Waiau and use the volcanic data as the initial field changes, we find that a 200 year integration time is required to match at best both records (Figure 1b). This corresponds to an 8–10 cm lock-in depth, which is not large but significant enough and confirms that even with rapid deposition rates sediment magnetization undergoes low-pass filtering.

The same Hawaiian volcanic sequence provides a partial description of field changes, but they are detailed enough to allow investigation of the transformation of this signal by magnetization processes in sediments. We have, thus, simulated VGP successions that would be recorded by sedimentary sequences with deposition rates of 10 cm/kyr, 4 cm/kyr, and 2.5 cm/kyr. Note that the lower two values are typical of marine sequences that have been studied extensively to obtain records of polarity transitions and that there are few studied sedimentary records with deposition rates as high as 10 cm/kyr. Each data point in Figure 1c represents a VGP obtained from a 2.5 cm long cylindrical sample. The VGP positions are different from their initial configuration even for records with rapid deposition rates. Most low-latitude data points have disappeared and the longitudinal distribution of VGPs is different. We also investigated the effect of smearing caused by postdepositional reorientation over a 10 cm deep layer with a 10 cm/kyr deposition rate. In this situation, which is likely more realistic, the results depict a smooth succession of VGPs across 180° of longitude. This recording differs significantly from the actual field changes.

We can explore further the consequences of the low resolution that is inherent to sedimentary paleomagnetic signals by relying on CALS10k.1b, geomagnetic field model [*Korte et al.,* 2011]. We have simulated a complete reversal by decreasing the axial dipole intensity until it reaches zero and subsequently recovers with the opposite sign, over a 10,000 year period. From this succession of field changes, we computed equivalent sedimentary records for various deposition rates. In Figure 1d we show the typical case of a reversal simulated at the same location as the 16.7 Ma Steens Mountain record from Oregon [*Jarboe et al.,* 2011], which is also shown for comparison. The VGP path derived from the model is less complex than the Steens Mountain paleomagnetic record, likely because CALS10k.1b is built from the current archeomagnetic and sedimentary database [*Korte et al.,* 2011] and thus fails to describe in detail the local and rapid field changes that could exist during a reversal. Transitional VGPs obtained for a sequence with a deposition rate of 4 cm/kyr, which is typical of most sedimentary records, have a much smoother configuration than those of

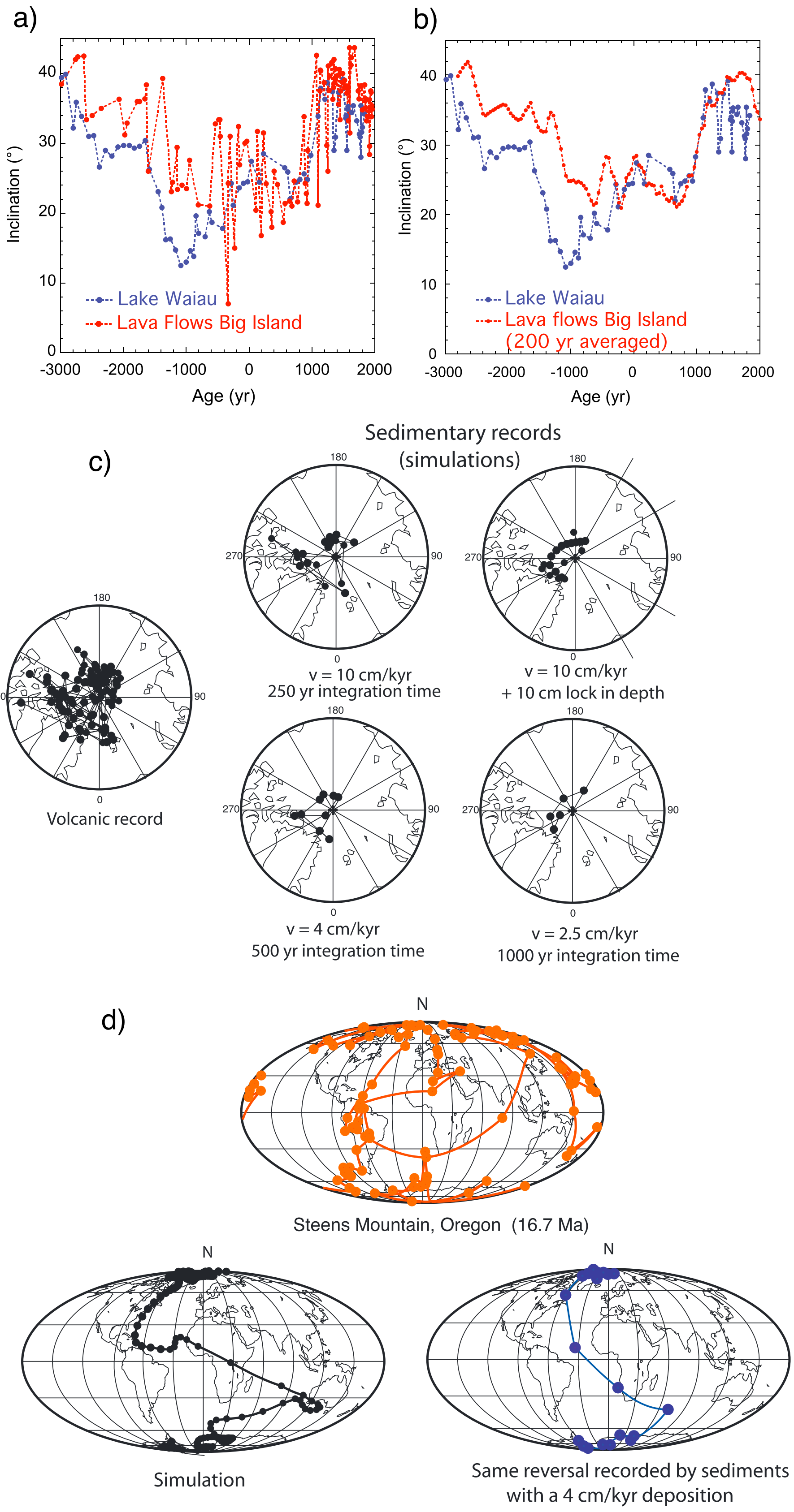
a)
Inclination (°)
40
30
20
10
0
-3000
-2000
-1000
0
1000
2000
Age (yr)
Lake Waiau
Lava Flows Big Island
b)
Inclination (°)
Lake Waiau
Lava flows Big Island
(200 yr averaged)
Age (yr)
c)
Sedimentary records
(simulations)
180
270
90
0
v = 10 cm/kyr
250 yr integration time
v = 10 cm/kyr
+ 10 cm lock in depth
Volcanic record
v = 4 cm/kyr
500 yr integration time
v = 2.5 cm/kyr
1000 yr integration time
d)
N
Steens Mountain, Oregon (16.7 Ma)
Simulation
Same reversal recorded by sediments
with a 4 cm/kyr deposition

Figure 1

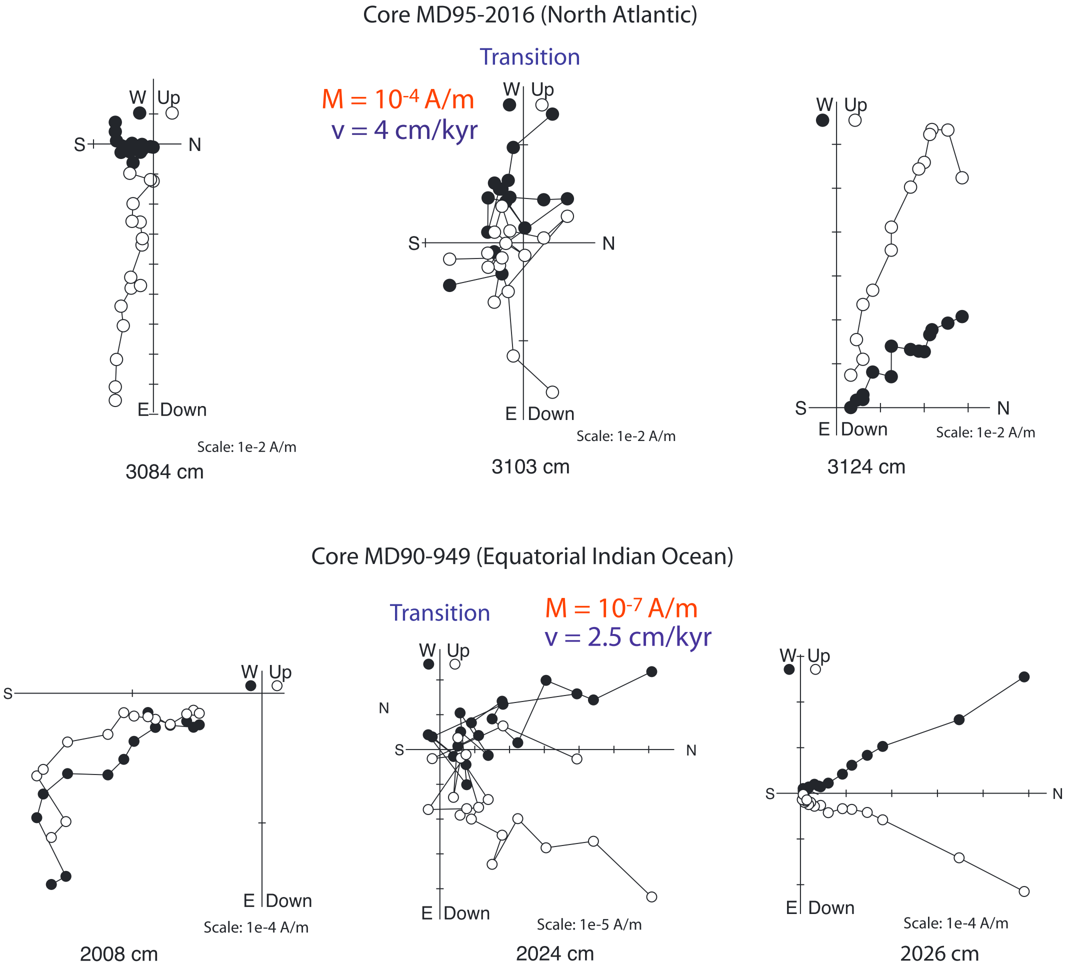

Figure 2. Typical demagnetization diagrams for samples from cores MD95-2016 and MD90-949 that recorded the last reversal. Diagrams in the middle panel correspond to transitional samples. Note that the large dispersion of successive directions prevents determination of a clear characteristic magnetization component. This behavior is encountered in most, if not all, reversal studies from sediments with deposition rates lower than 5 cm/kyr. It is most likely caused by overlapping of different directions.

the initial field. Additional smearing caused by postdepositional reorientation of magnetic grains further increases the tendency of transitional VGPs to be distributed along the same longitude in contrast to the 200° longitudinal crossing in the initial path.

2.3. Is the Weak Magnetization of Sediments Appropriate for Reversal Studies?

Time averaging inherent to the recorded remanent magnetization of sediments may generate another problem regarding definition of the characteristic component of magnetization that is isolated after demagnetization. In Figure 2 we show demagnetization diagrams for samples from two sediment cores in the Indian and North Atlantic Oceans, respectively. Outside the transition zones the characteristic components are well defined and decrease linearly to the origin of the demagnetization diagrams. Samples from the transition

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Figure 1. (a) Inclination changes recorded by volcanic and sedimentary sequences at the same location (big island of Hawaii) for the same time period. (b) Same as Figure 1a after time averaging the volcanic data within successive 200 year long windows. (c) Stereographic projections of VGPs that correspond to the signal in Figure 1a recorded by sediments with different deposition rates; VGPs are plotted on the right-hand side. The top right plot illustrates the effect of progressive magnetization locking over a 10 cm interval. (d) (top) Volcanic reversal record from Steens Mountain, Oregon [*Mankinen et al.*, 1985]; (bottom left) simulation of polarity reversal at the Steens location governed by a nondipole field similar to the present field; (bottom right) VGP path of the simulation shown on the left-hand side recorded by sediment with a 4 cm/kyr deposition rate. Note the longitudinal VGP confinement that is typical of many sedimentary records.

zones have constrasting behavior. Beyond the first demagnetization steps, there is no clear univectorial component that decreases to the origin but a scatter of data points that prevents definition of an unambiguous characteristic direction. The magnetization of the North Atlantic Ocean transitional samples is almost 1000 times larger than that of the Indian Ocean sediment, and thus is also much larger than for paleomagnetically well behaved nontransitional samples from this location. Therefore, the magnetization level of samples cannot always be considered responsible for the poor definition of the characteristic component of magnetization of transitional samples. It likely results from the rapidity of geomagnetic changes in weak fields which generate multiple magnetization components. Each stratigraphic level records different field orientations that are mixed within the sample. These components are likely carried by grains with similar coercivities, and it is, therefore, impossible to isolate a unique transitional direction. This situation generates erratic paleomagnetic behavior that is frequently encountered in transitional demagnetization diagrams for sediments. Noisy demagnetization results do not always preclude extraction of a characteristic magnetization component, but the validity of results is then questionable. *Roberts and Winklhofer* [2004] explained why most sediments fail to provide records of geomagnetic excursions as a consequence of postdepositional reorientations. The present scenario does not require any convolution of the signal caused by postdepositional remanent magnetization, since a 2 cm sample size is large enough to incorporate multiple magnetization components with the relatively low deposition rates inherent to most records.

To summarize, there are strong reasons to consider that the processes involved in magnetization acquisition in sediments are not appropriate for recording rapid field changes that are expected during reversals. Notwithstanding, we can ask whether sedimentary records remain useful for documenting long-term transitional field features.

2.4. Spot Readings of the Geomagnetic Field From Volcanic Records

In contrast to sediments, thermoremanent magnetization acquisition by lava flows is well understood and described by theory [*Néel,* 1955] so that in principle there is little doubt concerning the suitability of the signal. It is an instantaneous process that allows records of the total local field, including its dipole and nondipole contributions. There is no time averaging of field changes, and lavas offer the opportunity to determine the absolute field intensity for ideal samples. Despite these arguments, lava flows are not exempt from problems associated with paleomagnetic recording. As discussed below, some puzzling observations in transitional lava flows remain poorly understood and are likely to be the focus of much attention in the upcoming years.

Another factor is the effect of deviations of the local field by topographic features. They are enhanced during periods of weak field intensity [*Valet and Soler,* 1999] and can generate additional dispersion of paleomagnetic directions. Sampling over a large area within each flow is the best approach to detect and eliminate the contribution of such anomalies.

The major difficulty for high-resolution studies is that volcanism is sporadic in nature with lava flows irregularly distributed in time. For this period and a fortiori for older reversals, no dating technique is accurate enough to constrain the exact timing of eruptions, because the error bars on ages (even in the ideal situation of a well-dated sequence) exceed the duration of the reversal. We are, thus, faced with a compromise between obtaining a good quality paleomagnetic record and irregular eruption frequency. For this reason, sparse lava flows are not appropriate for reversal studies in the absence of chronological order and only sequences of superposed flows can be trusted to avoid confusion regarding their temporal succession.

3. Exploring Field Geometry During the Last Reversal

3.1. First Results Supporting a Nondipolar Transitional Field

The presence of weak magnetization intensities during transitional periods led rapidly to the concept that the field may lose its dominantly dipolar geometry while reversing. If the field remains dipolar during the transition between the two polarity intervals, the VGP paths of the same reversal recorded from distinct locations should be identical. A first compilation of 23 transitional intervals from volcanics heavily biased to Icelandic records was presented by *Dagley and Lawley* [1974], who reported a large diversity of pole paths that lent support to a model in which the nondipole field becomes dominant during a transition. Notwithstanding, the authors also noticed similarities between trajectories that could support a dipole model. Clearly, this compilation could not yield any definite conclusion in the absence of multiple geographically distributed records of the same reversal.

The M-B reversal is by far the best candidate for detailed analysis because it is identified unambiguously in sediment cores. Recent studies defend that the midpoint of the last reversal occurred at about 773 ka ago [*Channell et al.*, 2010; *Valet et al.*, 2014], which is consistent with recent U-Pb zircon ages at 770.2 ± 7.3 ka [*Suganuma et al.*, 2015]. As mentioned above, sediments are primarily sensitive to the dipole field. Therefore, they should be appropriate for determining whether the field remains dipolar. Following the pioneering reversal studies mentioned in section 1, *Hillhouse and Cox* [1976] compared VGP paths of the last reversal from sediments of the dry Lake Tecopa (California) and from Boso Peninsula (Japan) [*Niitsuma,* 1971]. The two trajectories are located within different longitudinal sectors and thus could not be reconciled with a dipolar transitional field. This data set was initially considered as the first tangible indication of the nondipolar nature of the geomagnetic field during the last reversal. However, two subsequent studies [*Valet et al.,* 1988b; *Larson and Patterson,* 1993] revisited the Tecopa sediments and revealed that the transitional directions are affected by viscous and chemical remagnetizations and are, therefore, not reliable records. This first test [*Hillhouse and Cox,* 1976] has never been validated from the two sites in question.

Many records of the last reversal have been subsequently acquired from marine sediments (see *Laj et al.* [1991], *Clement and Kent* [1991], *Clement* [2004], *Valet et al.* [1992], *Love and Mazaud* [1997], *Leonhardt and Fabian* [2007], and *Ingham and Turner* [2008] for compilations). These compiled VGP paths are from different geographical locations and, therefore, support a nondipolar transitional field geometry. However, the records were mostly obtained from sediments with deposition rates that did not exceed a few cm/ka. Can we claim that the transitional field lost its dipolar character from such low-resolution records? This question cannot be addressed without checking how far magnetization processes can affect transitional directional records. Assuming a deposition rate of 4 cm/kyr, a 1000 year transition will be integrated over the thickness of two samples and even much less in the presence of postdepositional magnetic grain reorientation. In this case, nonantipodal prereversal and postreversal directions are mixed with transitional directions and evidently fail to indicate the pristine field orientation [*Rochette,* 1990; *Langereis et al.,* 1992]. However, it is difficult to envisage that this smoothing process could reconcile VGP paths that were originally distinct from each other; this scenario seems unlikely for a large number of sites. Thus, apart from potential problems with isolating a suitable characteristic magnetization component, the tests of dipolarity should be valid when using sedimentary paleomagnetic records.

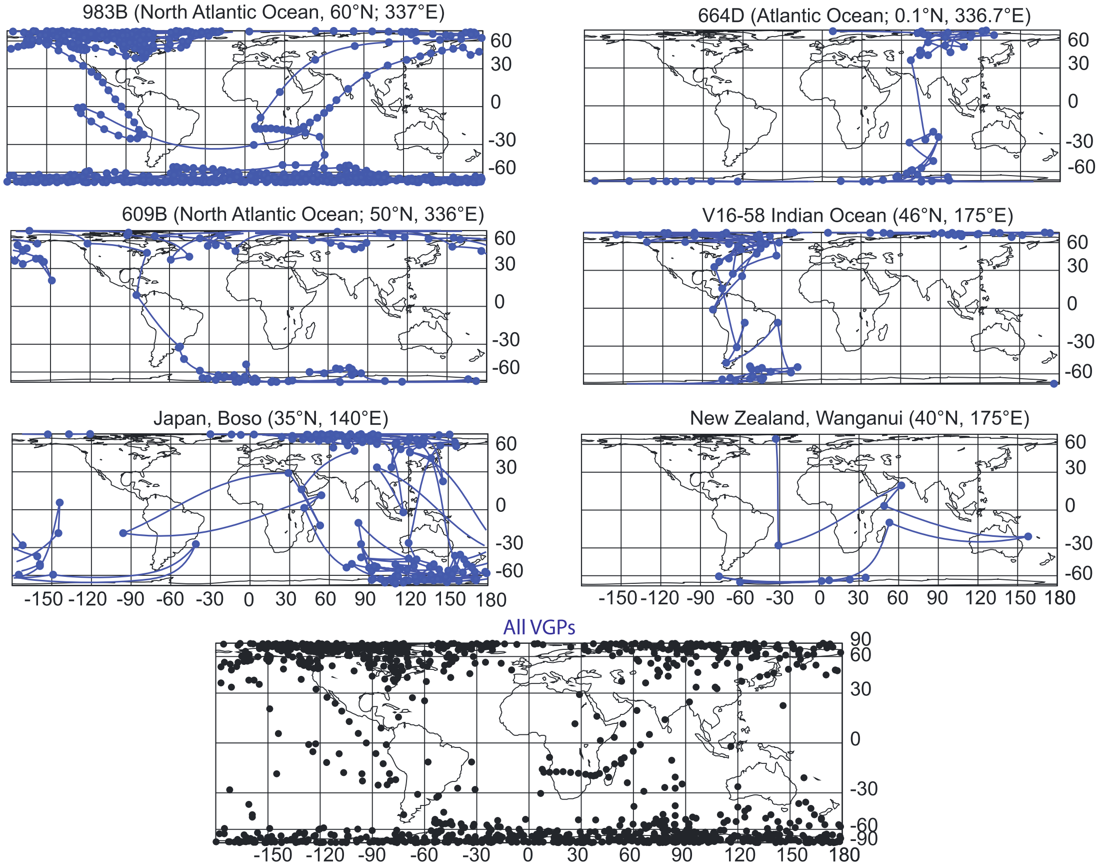
Other factors also affect VGP paths and especially their longitudinal configuration. Particles at the sediment-water interface can have their long axes parallel to the bedding plane and generate an inclination error [*Deamer and Kodama*, 1990; *Arason and Levi*, 1990; *Kodama*, 1997]. A first cause could be the flattening resulting from sediment compaction that reduces inclinations and induces a deviation of the magnetization vector away from the field direction. A direct consequence of such inclination errors is to bias pole positions away from the sampling site as described by *Barton and McFadden* [1996] who mentioned an equatorial longitudinal confinement of VGP positions. Another possible mechanism is that in the presence of weak transitional fields the geomagnetic torque is not strong enough to properly orient equant magnetic grains and leaves them with a poor if not zero net magnetization. The orientation process would then be governed by gravity and hydrodynamic forces so that the contribution of elongated particles with their long axes parallel to the bedding plane becomes dominant [*Quidelleur et al.,* 1995; *Heslop*, 2007].

To summarize, mechanisms linked to magnetization acquisition can artificially bias recorded VGPs, but it is difficult to create multiple VGP paths from the same dipolar field. Therefore, provided that the pristine origin of the magnetization has been established, the existence of different VGP paths from different sites most likely reflects a nondipolar character of the transitional field.

3.2. Database for the Last Reversal and Selection of Records

The first complete database of the last reversal was assembled by *Love and Mazaud* [1997] from 62 studies. Based on their own selection criteria the authors retained 10 records, six from sediments from Weinan, China [*Zhu et al.,* 1994], Boso Peninsula, Japan [*Okada and Niitsuma,* 1989], Wanganui, New Zealand [*Turner and Kamp,* 1990], Hole 609B in the North Atlantic Ocean [*Clement and Kent*, 1987], Hole 664D in the equatorial Atlantic Ocean [*Valet et al.,* 1989], and core V16-58 from the Southern Hemisphere [*Clement and Kent,* 1991]. Four volcanic records were also selected from Tahiti [*Chauvin et al.,* 1990], Hawaii [*Baksi et al.,* 1992], Matuyama-Brunhes

a) Sediments



b) Volcanics

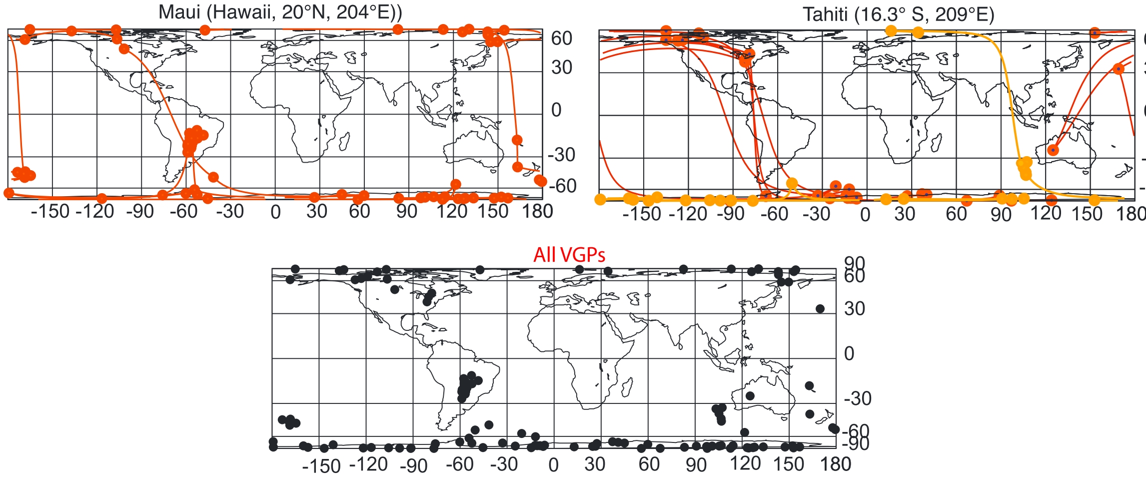


Figure 3. (a) VGP paths for the M-B transition derived from the updated *Love and Mazaud* [1997] database (see section 3.2) for sedimentary records—some line connections are not meaningful due to a lack of detailed successions of transitional VGPs. Note the smearing of directions and hence of VGP positions caused by U-channel measurements at Site 983. (b) Updated database for volcanic records of the last reversal. The bottom plot contains all VGP positions from the two sites.

Tongjing, China [*Zhu et al.,* 1991], and Chile [*Brown et al.,* 1994]. Any selection of records is subjective because it relies on debatable issues. In the present case, we dispute the choice of *Love and Mazaud* [1997] in relation to transitional samples that were not stepwise demagnetized (Boso Peninsula and Ocean Drilling Program (ODP) Hole 609B) and sedimentary records with deposition rates of 4 cm/kyr (ODP Holes 609B and 664D), which provide a highly smoothed picture of the transitional field. A few other records are also questionable regarding their interpretation. One site from a loess sequence is of doubtful value given the complex remanence acquisition mechanism in loess [*Zhao and Roberts*, 2010; *Wang and Løvlie*, 2010; *Taylor et al.,* 2014]. Five sedimentary sites have deposition rates between 4 and 6–8 cm/kyr. All of these VGP trajectories are poorly defined with only two or three VGPs, such as the puzzling record from Boso Peninsula [*Niitsuma*, 1971] with few intermediate VGP positions, despite a deposition rate 40 times as large as that at the other sites.

Based on these considerations, we retained the five remaining sedimentary records of *Love and Mazaud* [1997] to which we added more recent data from the North Atlantic Ocean [*Channell et al.,* 2004]. Each VGP path has been plotted separately in Figure 3a. The dominant characteristic is that they are all different and, thus are consistent with a nondipolar transitional field. The second characteristic is that complexity increases with the resolution of the records. This is particularly true for the Japanese and North Atlantic sites that have much faster sediment accumulation rates. In contrast, the VGP trajectories from sites ODP Holes 664D and 609B are poorly defined due to their low deposition rates and, therefore, provide a smeared recording of the geomagnetic signal.

We have proceeded the same way to select volcanic records of polarity transitions. We now know that the volcanic record from Chile [*Brown et al.,* 1994], which has been redated [*Singer et al.,* 2005], is not related to the last reversal. Furthermore, the study from Tanjing, China [*Zhu et al.,* 1991], incorporates only three data points from three lava flows and a sole transitional direction. The same concern exists for the unique intermediate VGP position common to a sequence of five flows from Tahiti [*Chauvin et al.,* 1990]. We dispute that this VGP cluster resulted from a short period of volcanic activity and consider it, therefore, as not fully representative of the reversal process (see sections 4.4 and 4.6). We add two recent volcanic records of the last reversal that were not incorporated in the former database [*Love and Mazaud,* 1997]. The first [*Coe et al.,* 2004] is from Maui (Hawaii), while the second [*Mochizuki et al.,* 2011] from Tahiti (french Polynesia) completes a former data set [*Chauvin et al.,* 1990] from this location. Figure 3b incorporates about 20 volcanic VGP positions at latitudes <45° with no longitudinal preference and no similar VGP position among the records. We deplore the existence of such a relatively sparse data set. Despite this limitation, these VGP configurations are inconsistent with a dipolar transitional field.

3.3. Additional Indications for a Nondipolar Transitional Field

Other studies have reinforced the hypothesis of a nondipolar transitional field and that nondipolar field configurations could have dominated during reversals other than the last one. Simple geometrical reversal models, in which nondipole fields are allowed to persist while the axial dipole decays through zero and then builds again in the opposite direction, predict increased reversal duration with latitude, a trend that has also been reported in the numerical simulations [*Wicht,* 2005; *Wicht et al.,* 2009]. The average trend is not monotonic, with duration decreasing from the equator to the tropics and increasing again en route to the pole (e.g., Figure 4.18 in *Wicht et al.* [2009]). This reflects the fact that the duration of some simulated reversals does not have a clear longitudinal dependence.

Despite our lack of confidence in sedimentary records, we report an observation by *Clement* [2004] who selected sediment records of the last four reversals and found that the apparent duration of the transitional interval (which represents the thickness of sediment with transitional directions) varies with site latitude. However, this implies that similar processes governed all four reversals and that they had the same duration at each latitude. This is a major assumption which, given the small size of the database, cannot be tested. For this reason, we have restricted our analysis to the last reversal. The picture that emerges from Figure 4a is incomplete with only three Southern Hemisphere sites (that have been plotetd with positive latitudes). Shorter durations are observed in records from low-latitude sites along with longer durations at middle to high latitudes, but the relationship is not without ambiguity due to data scatter. If we take into account the sizes of the error bars, there is roughly a factor of 2 difference in mean duration at sites below 20° latitude and those between 30° and 60°, but there is no clear trend within these two latitudinal groups.

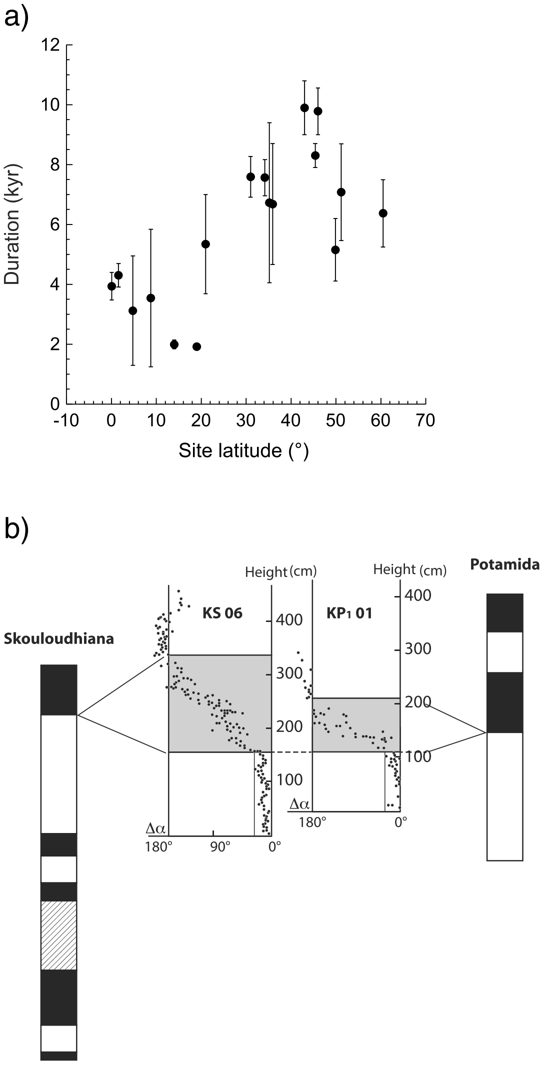


Figure 4. (a) Duration of the last reversal derived from sedimentary records [*Clement*, 2004] as a function of site latitude. (b) Thickness of transitional intervals (black intervals) that corresponds to the same Miocene reversal recorded in adjacent sedimentary sequences from Crete.

Care should be exercised when dealing with mean deposition rates to calculate durations of short events. Deposition rates can vary rapidly over time intervals as short as a few thousand years. A typical example is provided by a study from Crete [*Valet et al.,* 1988a] with two distinct records of the same reversal from sites located a few kilometers away from each other (Figure 4b). The mean deposition rate [*Langereis et al.,* 1984] of section 1 (Potamida) is 1.3 times larger than that at section 2 (Skouloudhiana), but the transitional interval at section 2 is inconsistently twice as thick as that at section 1. The apparent duration of the transition, therefore, differs by almost a factor of 3 between these nearby sections; this cannot be due to the field. The recording differences observed for these neighboring sections with the same environmental conditions could also occur for sections separated by thousands of kilometers and limits analysis of transitional records. Another factor to consider is the complexity of the process associated with precursory and/or rebound phases within a transition with significant duration (see section 6.1). At low deposition rates these phases can be mixed in the record or at least generate large biases. In the study of *Clement* [2004] low- and high-latitude records are both characterized by different deposition rates; therefore, the relationship found by the author must imply the absence of correlation between the thickness of transition zones and deposition rates if it is field dependent. This has been tested and gives further credit to the results. It is impossible to establish the chronology for transitional superimposed lava flows and, therefore, such records are not compatible with the approach of *Clement* [2004]. Notwithstanding that, if we refer to the short period during which the VGP transits between the two geographic poles, the few high-latitude records contain more intermediate directions than low-latitude ones. Keeping these restrictions in mind, we are tempted to favor a latitudinal dependency of reversal duration, but a larger number of records, particularly with deposition rates between 6 and 12 cm/kyr, remains crucial to validate the relationship firmly.

3.4. Modeling the Harmonic Content of the Transitional Field

A primary goal when studying reversals is to determine the harmonic content of the transitional field. Four attempts have been made so far. It is not surprising that all studies have focused on the last reversal. In addition to the need for good quality directional and paleointensity variations, a major difficulty is to establish the simultaneity of field changes recorded from remote places in order to align all events on a common time scale. The task is even more difficult because nondipolar field components are supposed to generate different field changes depending on location.

Mazaud [1995] sought the best correlation between VGP latitudes recorded at different sites. He assumed that VGPs cross the equator simultaneously at all sites. However, given that a nondipole field likely governs transitions, this assumption will not be valid [*Quidelleur and Valet,* 1996; *Brown et al.,* 2007; *Valet and Plenier,* 2008], even with a static nondipolar field.

Shao et al. [1999] followed another approach using a scheme based on Maxwell's multipole theory. They used the database compiled by *Athanassopoulos et al.* [1995] for the last reversal, which was an exhaustive compilation of all reversal studies without any selection and is therefore governed by a majority of meaningless low-resolution sedimentary records.

Leonhardt and Fabian [2007] used an original approach based on an iterative Bayesian scheme to construct a global model of the MB transitional field up to spherical harmonic degree 4. The model describes the field evolution derived from four studies (ODP holes 664D, 609B, core V16-58 for sediments, and the ME-ET sections for volcanics). In a second step, the field changes predicted at several other locations are tested against existing records at the same locations. This approach appears suitable; however, we again question the choice of the database. The records from sites ODP Hole 664 and core V16-58 have low resolution with deposition rates from 4 to 2.5 cm/kyr and few transitional data points, while the volcanic sections ME-ET at La Palma do not incorporate any transitional directions and therefore bring no constraint to the problem.

The model of *Leonhardt and Fabian* [2007] has been tested by comparing its predictions against eight other independent records from different geographical locations. Even complex VGP movements are remarkably well predicted for most independent sites, but these optimistic conclusions cannot be validated. The record from ODP site 792 (Northwest Pacific Ocean) includes only two transitional VGPs and is, therefore, not testable. The record from site RC15-21 has a deposition rate as low as 1.1 cm/kyr, which is not suitable for a reversal study. Note also that the data from ODP Hole 883B [*Athanassopoulos et al.*, 1993] have never been published and are in full disagreement with the model prediction. Moreover, the authors incorporated results from the LL section at La Palma [*Quidelleur and Valet,* 1996] that are not related to the last reversal, and from Lake Tecopa which, despite fair agreement with the model, has been shown to be remagnetized [*Larson and Patterson,* 1993]. The fact that the model predictions can be defended from inadequate data is puzzling. Not only does it emphasize the need to select appropriate data with regard to objectives but it also points out a great deal of subjectivity when comparing model predictions.

The most recent global model of the last transition goes up to degree 3. It was attempted by *Ingham and Turner* [2008] from 11 records but only from 10 distinct sites, considering that two records (ODP sites 983 and 984) are from nearby localities in the North Atlantic Ocean [*Channell and Kleiven,* 2000; *Channell et al.,* 2004]. Five records were included while two others were rejected from the compilation by *Love and Mazaud* [1997] based on lack of resolution. The three remaining records are from more recent studies, but they are hampered by problems that limit their usefulness. The first record was obtained from California margin sediments and was described by the authors [*Heider et al.,* 2000] as being affected by a strong coring-induced overprint that gave rise to false transitional directions. In addition, VGPs for the normal and reverse polarity directions that surround the reversal do not reach the geographic North and South Poles. The second record from rapidly deposited sediments cored in the Celebes and Sulu Seas [*Oda et al.,* 2000] incorporates only two intermediate directions with equatorial VGPs and no data between the North Pole and South Pole positions due to the scarce sampling. Lastly, a record from ODP Hole 1082C in the South Atlantic Ocean [*Yamazaki and Oda,* 2001] was obtained from two data sets that yield different transitional results: the studied U-channel samples have many transitional directions, while the discrete samples define two successive phases with a precursor and a transition with few transitional data. The U-channels have smeared the signal and generated transitional directions that cannot be validated by the single-sample data. During the reversal, the dipole and axisymmetrical quadrupole change polarity while the other Gauss coefficients retain values close to those of the present field with some random noise. The Gauss coefficients that describe the model were then used to generate reversal data at the 10 sites that correspond to locations of studied reversal records, all from sediments.

In contrast to *Leonhardt and Fabian* [2007], *Ingham and Turner* [2008] compared a few predicted field changes with those derived from the corresponding paleomagnetic record. How far can we compare the predictions of these two models? They both find that through the reversal the dipole and nondipole fields had approximately equal intensities, which may result from the time averaging inherent to sedimentary records. The nondipole field appears to be weakened at some point in the former model, while this is not the case for the later model. The model of *Ingham and Turner* [2008] contains a large excursion prior to the transition that does not appear in the *Leonhardt and Fabian* [2007] model due to their choice of sites. It is puzzling that no dipole decrease accompanies the prereversal excursion. Except for a short period, the nondipole/dipole ratio is strikingly different between the two models.

4. Features of the Transitional Field

No complete documentation of transitional field behavior has yet been provided by paleomagnetic records. Therefore, results are often split between arguments that support a direct geophysical interpretation and those that question the suitability of the measured paleomagnetic signal. One can defend a consensus that emerges when a specific feature is documented repeatedly by records of various origins. Nevertheless, this is not straightforward because artificial features can be induced by the magnetization process and/or by inaccuracies in determining the timing of events. Controversies about the existence of preferred longitudinal VGP bands or the origin of directional clusters are typical cases that demonstrate this point.

4.1. Preferred VGP Locations

Among the earlier models proposed for reversals, *Bogue and Coe* [1984] suggested a standing field that persisted during successive reversals and, therefore, produced recurrent VGP trajectories when observed at the same site (the standing component being nondipolar). This concept of recurrent mechanisms over long periods of time was given a geophysical meaning after being further promoted in a different way as described below.

Although sediments fail to record rapid nondipolar field components, we cannot discard the concept that they retain a memory of persistent long-term geomagnetic features. *Clement* [1991] observed that sedimentary records of the last reversal are constrained within two “preferred longitudinal bands” almost 180° apart from each other. In the meantime *Tric et al.* [1991] and *Laj et al.* [1991, 1992] reached similar conclusions from a larger set of records distributed between the late Miocene and the last reversal. They noticed that the two longitudinal VGP bands correlated with regions of high seismic velocity in the lower mantle [*Dziewonski and Woodhouse,* 1987] and, thus, with cold and/or dense material at the base of the mantle. They also lie close to regions of magnetic flux concentrations in the historical field [*Bloxham and Jackson*, 1992; *Jackson et al.,* 2000]. For the first time, the concept of mantle control on the reversing field could be directly associated with paleomagnetic observations [*Gubbins*, 1994].

4.2. What Mechanism?

Before discussing the aspects related to the database of polarity transition records, the question that comes to mind is by which mechanism structural seismic anomalies constrain pole locations during reversals. Dynamical coupling between core and mantle would establish steady conditions at the core-mantle boundary (CMB) that would persist long enough to give rise to recurrent transitional field features. *Runcorn* [1992] proposed that electromagnetic torques originating from a heterogeneous electrical conductivity distribution in the lowermost mantle would tend to bias the weak transitional field toward mantle structures. This scenario was further studied by *Brito et al.* [1999] using an analytical model that included resistive torques in addition to the driving torques previously considered by *Runcorn* [1992]. This led *Brito et al.* [1999] to draw the opposite conclusion, namely, that lateral variation in lower mantle conductance was unlikely to affect the VGP path during a reversal. To our knowledge, this issue has not since been addressed using numerical simulations and may be worth reconsidering when further constraints are placed on the conductivity distribution in the lowermost mantle, particularly in connection with postperovskite phase transition [*Ohta et al.,* 2008].

Alternatively, and because mantle and core are heat engines operating on vastly different time scales, the heat flux imposed by the mantle on the underlying core at the CMB can be considered as being static when studying core dynamics on magnetic diffusion time scales (tens of thousands of years). Lateral variations of the heat flux imposed by temperature inhomogeneities in the lower mantle influence core flow. *Glatzmaier et al.* [1999] imposed a nonuniform heat flux pattern on a reversing dynamo model and found a crude correlation between the density of transitional VGPs and the pattern of heat flux at the CMB (their Figure 1d), an analysis based on a limited number of simulated reversals (see also the discussion in *Glatzmaier and Coe* [2015]). More recently, *Kutzner and Christensen* [2004] used a three-dimensional convection-driven numerical dynamo with imposed nonuniform CMB heat flow and found, based on a much larger number of reversals, that the VGPs have a tendency to fall around longitudes of high heat flow. They pointed out the role of the equatorial dipole in favoring longitudinal VGP bands. Stronger heat flow induces flow convergence and hence stronger magnetic flux, and therefore a preferred location (on average) for the equatorial dipole. As physically sound and satisfactory as this mechanism can appear, a caveat is that the heat flux heterogeneity must be large in the simulations, representing a significant portion of the heat conducted along the adiabat, for this geographical localization to be effective. Interestingly, VGPs in the present NAD field are found along the western Pacific rim [*Valet and Plenier,* 2008], but this large preference disappears after removing the equatorial dipole contribution. Given its permanent and rapid evolution (as directly observed from the archeomagnetic database) we can wonder by which process the equatorial dipole generates a long-term recurrent pattern, unless it is assumed that despite its permanent motion, the present orientation has been dominant over the past million years. The mechanism proposed by *Kutzner and Christensen* [2004] enables such long-term mantle control, but again, it is not certain because it requires large heat flux contrasts. These contrasts (expressed as a fraction of the heat conducted along the adiabat) become even more questionable as the recent increase in estimated core thermal conductivity has precisely multiplied by a factor of 2 to 3 the heat conducted along the core adiabat (see *Hirose et al.* [2013] for a review).

4.3. A Few Possible Artifacts

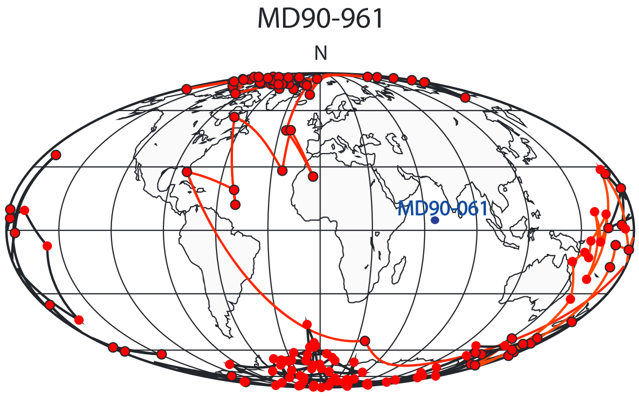
Most sites represented in the database are far from being uniformly distributed around the globe, but they, too, are concentrated within two antipodal longitudinal bands approximately 90° away from the preferred transitional VGP longitudes [*Valet et al.,* 1992; *McFadden et al.,* 1993]. Moreover, this initial compilation included a few controversial records such as a dominant VGP trajectory (in terms of the number of intermediate directions) that was recorded by the authigenic mineral greigite [*Tric et al.,* 1991] and is, therefore, not appropriate for transition studies [*Roberts et al.,* 2005, 2011]. Several scenarios, including nonantipodal stable directions before and after a reversal [*Langereis et al.,* 1992], as well as the influence of inclination shallowing [*Barton and McFadden,* 1996] or the enhanced role of gravity and hydrodynamic forces on settling magnetic particles (see section 3.1), have been raised to account for the two antipodal longitudinal bands. The debate is still alive, but a few other observations cast additional doubt about the geomagnetic origin of VGP paths found within preferred longitudinal bands.

It is striking that the most detailed records from the North Atlantic Ocean [*Channell et al.,* 2004] with deposition rate larger than 10 cm/kyr and those from Japan [*Okada and Niitsuma,* 1989] with deposition rate larger than 300 cm/kyr do not have longitudinally confined VGPs but successions of latitudinal and longitudinal crossings. The North Atlantic records also contain VGP clusters, but they could have been generated partially by signal smearing by the response curve of the magnetometer [e.g., *Nagy and Valet*, 1993; *Weeks et al.*, 1993] during continuous measurements of long sediment sections. This effect can be illustrated by comparing the directions measured by this technique with those obtained from a suite of single samples adjacent to each other from the same sequence. Directional changes associated with the last reversal measured at the same depths in U-channels and single samples from core MD90-961 have marked discrepancies (Figures 5, top and 5, bottom). The VGPs derived from the U-channels are more concentrated than those of the single samples and contain clusters that are not so strongly present in the single-sample data. This is a consequence of measurement smearing. Evidently, the characteristics of the record can vary because the volume of sediment integrated by continuous measurements is much larger than for single samples. Some results from ODP Site 983 demonstrate that U-channel measurements have filtered large-amplitude changes revealed by single samples, so that at some stratigraphic levels the results differ by up to 40° in inclination (see Figures 10–12 in *Channell et al.* [2004]).

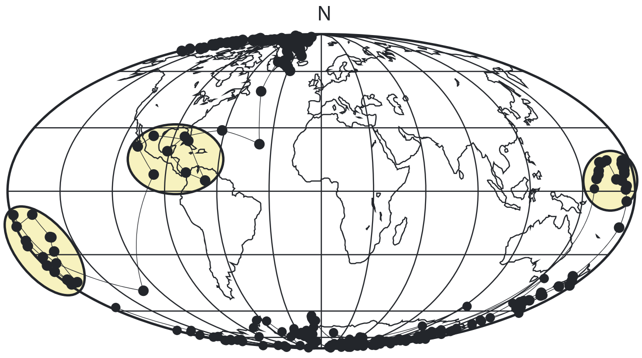
The overall similar configuration of VGP paths of three distinct North Atlantic records pleads in favor of their geomagnetic origin. However, the detailed directional changes differ between the three records. The complexity of the North Atlantic VGP trajectories contrasts sharply with the smooth aspect of VGP paths obtained for records from sediments with lower deposition rates. The resolution of the records from rapidly deposited sediments is high enough to resolve rapid time-varying nondipole components during the transition, while the lower resolution records have been time-averaged.

4.4. Long-Lived Transitional Field States: The Geomagnetic Scenario?

There is little evidence for continuous VGP movement in volcanic reversal records. Concentrating on a selection of six data sets from five sites over the past 10 Ma, *Hoffman* [1991, 1992] reported the existence of two transitional VGPs clusters; one centered over western Australia and the other one off the southeast coast of western America. They were both interpreted as reflecting specific inclined dipolar field configurations. In a



Single sample measurements



U-channel measurements

Figure 5. Comparison of VGP paths derived from measurements of (top) single samples with those obtained from (bottom) U-channels at the same spatial resolution. Note the emergence of VGP clusters (yellow areas) generated by smearing introduced by the response function of the magnetometer for U-channel measurements.

subsequent paper concerning the last reversal, *Hoffman* [2000] described the dominance of two pairs of low- and middle-latitude VGP concentrations that are mirrored about the equator and concluded that the M-B reversal was dominated by quasi-stationary low harmonic order states. It was proposed that a transitional state was reached early after the transition onset, held for a considerable time, and that the reversal was rapidly completed much later. The VGP clusters are possibly connected to the apparent preferred longitudinal VGP bands observed in sediments, because smoothing inherent to magnetization acquisition generates longitudinally confined transitional VGPs by the smearing of clusters that lie within or close to the preferred longitudinal bands.

Two issues lie behind the concept of long-lived transitional field states that we discuss separately. The first concerns the origin of clusters within a single reversal, while the second is related to the recurrence of the same clusters during different reversals.

The presence of a patch of recurring VGPs during a reversal suggests that the geomagnetic field retained the same inclined dipolar configuration for a certain period of time provided that the patch is observed globally. This interpretation relies on the assumption that each individual lava flow provides a unique and independent record of the local field. However, successive flows with the same direction can also be generated by closely spaced eruptions. In this case, VGP clusters would represent a unique, almost instantaneous, picture of the field. The "volcanic" hypothesis assumes that directional clusters result from rapid successive eruptions, whereas in the "geomagnetic" scenario the field remained stable for a long period of time. It is impossible to test the two hypotheses using radiometric dating. If we refer to the historical field, the rate of geomagnetic changes varies with time and location. The recent geomagnetic declination has changed in Europe by 10° in about 80 years, which can be considered as a lower limit of resolution for paleomagnetic records. Thus, redundant directions can be recorded over a few hundred years, which is compatible with the frequencies of volcanic eruptions.

4.5. Long-Lived Transitional Field States: The Volcanic Scenario?

No unambiguous test exists to discern whether VGP clusters reflect intense volcanic activity or standstills in the geomagnetic reversal process. In principle, the same weight must be given to both hypotheses. However, volcanic activity is characterized by periods of quiescence followed by periods of intense activity and reports of historical eruptions suggest that the volcanic explanation makes sense. The existence of VGP clusters has also been reported in a few sedimentary records but their interpretation can be subjective. A typical example is the record of the Gauss-Matuyama reversal from the sediments of Searles Lake (California) [*Glen et al.*, 1994, 1999], if we exclude the possibility that potential coring disturbances generated large directional changes interpreted as excursions like in another core drilled at Owens Lake using the same technology [*Rosenbaum et al.*, 2000]. The VGP path has been described as a succession of clusters, but it can as well be interpreted as a continuous and regular VGP evolution punctuated by short variations in deposition rate. Surprisingly also for the CMB control hypothesis, one of the clusters lies above North Africa which is above a zone of slow lower mantle shear wave velocities, while, according to the data and models mentioned above, VGPs are expected to fall above zones of high heat flow and, therefore, fast shear wave velocities.

If clusters represent long-lived transitional field states, they must have lasted long enough to have a chance of being documented in most, if not all, sequences that recorded the same reversal. A few reversals recorded in parallel sequences of superposed volcanic flows that are only a few kilometers away from each other provide interesting indications as discussed below. The first study of *Van Zijl et al.* [1962] of a reversal recorded by the Stronberg lava flows in South Africa has been reinvestigated at another locality by *Prévot et al.* [2003] and more recently by *Moulin et al.* [2012]. Three parallel sections reveal the same dynamical structure, and particularly the existence of a large elongated loop with VGPs that cluster to the southeast of Asia. However, none of the three records have the same number of stationary poles, whereas VGP clusters at the same location in the three sections should reflect a long stationary field state if the same flows are present. The other example involves the Steens Mountain reversal data set, which is the most detailed volcanic record of a reversal. It contains a series of VGP clusters recorded from sections 60 km apart by lava flows with different chemistry. In addition, one VGP cluster (located in western South America) is visited twice early and late in the record, which reinforces the concept of a correlation with the fast seismic velocity zone beneath this area, although it is puzzling that the same record also contains a cluster over North Africa again above a zone of lower mantle low shear wave anomalies.

Two other studies of parallel volcanic sequences have been connected to each other to provide additional information. An intriguing observation in favor of episodic volcanism comes from the record of the Upper Mammoth transition [*Herrero-Bervera and Valet,* 1999, 2005] from several nearby sequences in Waianae volcano (Hawaii). Each sequence records different VGP distributions, which sometimes cluster at the same location with a different number of lavas and sometimes not, while they are separated by a few kilometers at most. Similarly, a link between transitional directions and volcanic activity can be derived from parallel Icelandic sections that recorded the R3-N3 reversal which likely corresponds to the Matuyama-Réunion reversal. The sections were initially studied by *Sigurgeirsson* [1957] and *Wilson et al.* [1972], and they have been subsequently revisited by *Goguitchaichvili et al.* [1999]. The evolution of VGP latitude plotted in Figure 6 reveals that each section records the same geomagnetic features but that the VGP cluster found close to the equator is different in each sequence. Of particular interest is the relationship between the resolution of the cluster and the geographical location of each sequence. The most detailed cluster was obtained at section PV likely close to the eruptive center and the number of clustered VGPs decreases with distance away from section PV. At the farthest location away from PV, section KY has a relatively regular VGP distribution while section SB did not record any intermediate VGP. Distance from the eruptive center was the unique factor that controlled the number of lava flows produced during this period. If we assume that these successive lava flows covered a long period during a stationary field state, there is no reason why it would not be recorded at least once. We infer that these records with clustered VGPs were generated by rapid eruption frequency and that they were controlled by the size of the event which likely reflects gradual depletion of the magma chamber.

Another point to consider in relation to transitional VGP clusters is the apparent recurrence of a few spots (like Australia) mentioned in some studies that are discussed below. Evidence for recurrence of the same VGP cluster recorded from distant sites during the same reversal would provide evidence for a geophysical origin of each cluster.

4.6. Are VGP Clusters Related to Field Anomalies?

Hoffman and Singer [2008] related the most intense geographical flux lobe of the present NAD field over Australia to the location of the VGP cluster derived from a selection of transitional data at Tahiti to argue for long-term field anomalies that are important for transitional fields. If we refer to the NAD during the past thousand years and not only the past 100 years as considered by *Hoffman and Singer* [2008], there is no evidence for persisting stationary features. Flux lobes exist, but they appear and disappear. This might, however, reflect the type of prior information used to build time-dependent geomagnetic field models over the past few millennia (see *Korte and Holme* [2010] for details). *Hoffman and Singer* [2008] noticed that in contrast the VGPs of an excursion recorded from the Eiffel volcanics are spread over Eurasia, because this locality is

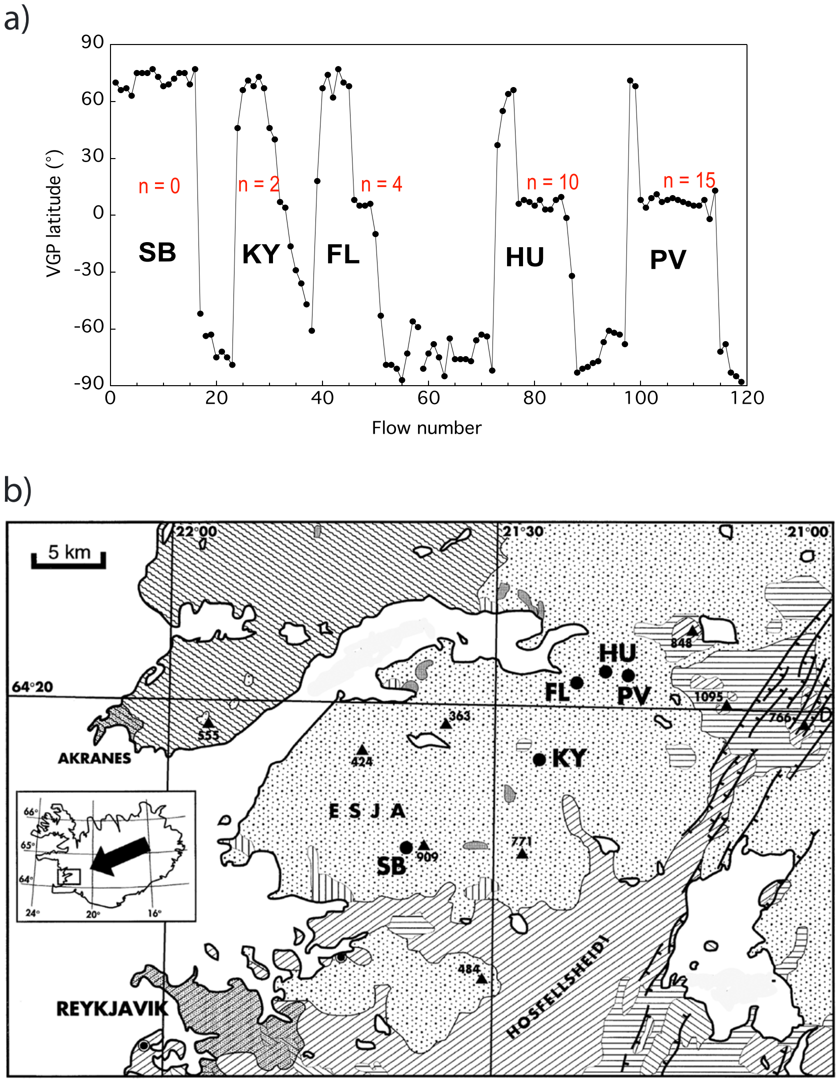


Figure 6. (a) Evolution of VGP latitude recorded in five parallel sequences of overlying lava flows. In each case a group of VGPs is present at the same low-latitude position, but the number of VGPs differs between each sequence. (b) The decreasing number of VGP positions depends on the distance of the flow from the eruptive center, which is close to location PV. Redrawn from *Goguitchaichvili et al.* [1999].

located far from the influence of prominent concentrations of NAD field flux. In both cases, the authors argued that the NAD field dominated the transition and resulted from motions generated in Earth's upper core. The field pattern is argued to have been controlled strongly by physical variability of the lower mantle. This suggestion implies that a given cluster should be observed during successive events at the same geographical locality, but not from everywhere.

Support for these concepts relies on a subset of paleomagnetic records but ignores the rest of the database. We selected the detailed volcanic records from sequences of superposed lava flows including at least five distinct transitional VGP positions and several reversed and normal polarity flows surrounding the reversal. Only 10 records satisfy these criteria that guarantee that we are dealing with actual reversal records without uncertainty about the chronological succession of events. The individual VGP paths are shown in Figures 7a–7k. The number of intermediate VGPs remain poor to draw firm conclusions. In the present state of the database, we can simply mention that there is no systematic reproduction of VGP clusters over Australia and America and that clusters are also present at other locations like central Europe, mid-North Africa, and the mid-South Pacific which are neither linked to preferential longitudinal bands, nor to long-term field anomalies. More

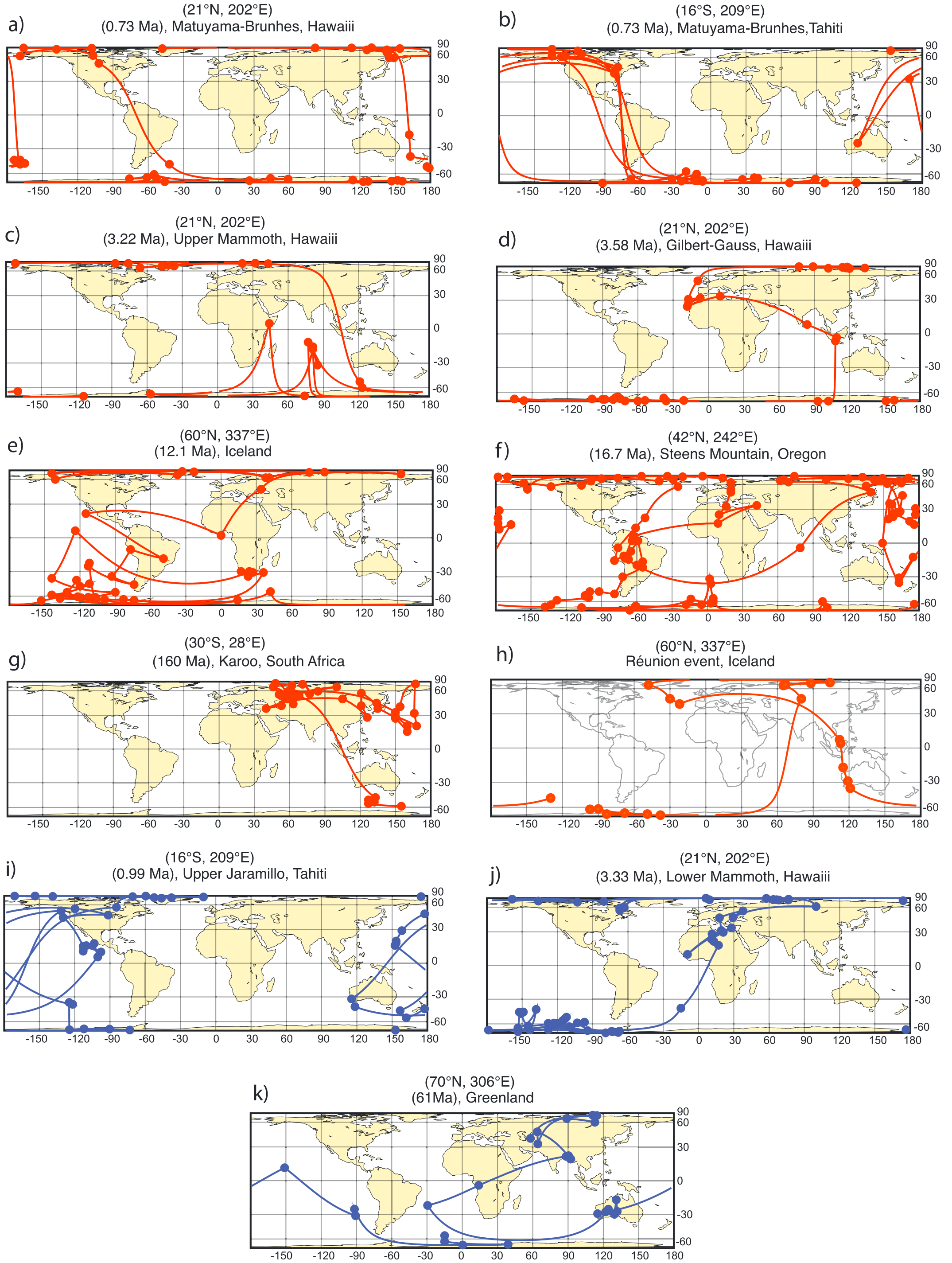


Figure 7. (a–k) VGP paths of the most detailed volcanic records of reversals. Red (blue) VGP paths correspond to reverse-normal (normal-reverse) transitions. Data are from: *Coe et al.* [2004], *Chauvin et al.* [1990], *Mochizuki et al.* [2011], *Herrero-Bervera and Valet* [1999], *Herrero-Bervera et al.* [1999], *Moulin et al.* [2012], and *Riisager et al.* [2003].

specifically, the two detailed volcanic studies of the last reversal shown in Figures 7a and 7b, which were not included in the *Hoffman and Singer* [2008] analysis, do not indicate the existence of VGP clusters.

Four records contain VGPs in the vicinity of Australia. The most significant groupings are present for the Réunion event (2.2 Ma) recorded in Iceland (Figure 7h) and in the 61 Ma reversal from Greenland (Figure 7k). The other two clusters concern the M-B transition with one VGP over Australia and the Upper Jaramillo (0.99 Ma) from

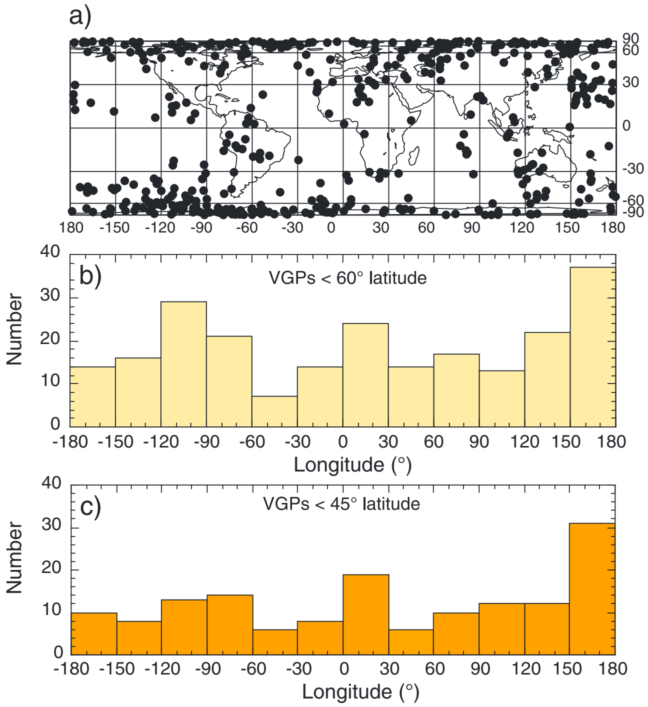


Figure 8. (a) VGP positions of the volcanic reversal records shown in Figure 7. (b) Histogram of the frequency of VGPs in terms of longitude. (c) Same as Figure 8b but for VGPs with latitude lower than 45°.

Tahiti with two VGPs over Australia, which, therefore, cannot be considered clusters. We could add the Big Lost event pointed out by *Hoffman and Singer* [2008] (but this record does not satisfy our selection criteria) that contains "Australasian" VGPs according to the name given to this patch. Altogether these results are at first glance neither consistent, nor fully inconsistent with the suggestion of *Hoffman and Singer* [2008]. However, we should expect VGP clusters in the records from Hawaii, but they are not present. In contrast, no Australasian cluster should be observed in the high-latitude records, yet such directions occur in the too high latitude records.

The hypothesis of preferred VGP paths has been tested several times using volcanic records. The conclusions of *Prévot and Camps* [1993] defending the proposed uniform distribution of transitional volcanic VGPs were dismissed by *Love* [1998]. Although the two databases used for the respective analyses were more or less the same, the data treatments were different, which again raises questions about field sampling by lava flows. *Prévot and Camps* [1993] considered similar directions to mostly coincide in time and, thus, must be combined into a single direction, while *Love* [1998] defended the opposite. A second difference was that *Love* [1998] weighted the data to account for the fact that transitions are recorded by widely differing numbers of intermediate directions. This approach was initially followed for sediments [*Valet et al.*, 1992] to compensate for differences (sometimes up to a factor of 30) in resolution between individual records and also because field changes are heavily smoothed by the magnetization acquisition process. Most trajectories are longitudinally constrained, so that the weighting procedure does not introduce any change in the final information with respect to a nonweighted detailed trajectory. However, the VGP paths of the most detailed volcanic records are complex and therefore contain significant geomagnetic information that is truncated and, thus, lost after weighting. The weighting procedure is, therefore, questionable for volcanic records, especially when VGPs are scattered over the globe. Lastly, it is worth mentioning that most VGPs in the compilation have high latitudes (say between 50° and 60°) and are not representative of a transitional state.

In Figure 8 we plot all intermediate volcanic VGPs (Figure 8a) (from the previous selection of records) with a frequency histogram within 30° longitudinal bands after selecting VGP latitudes $<60°$ (Figure 8b) and $>45°$ (Figure 8c). The VGP positions are widely scattered and lie within all longitudinal bands. Higher frequency is found within the 60° to 120°W sector over the American continent, which is caused by a group of VGPs at northern intermediate latitudes in the Steens Mountain record [*Jarboe et al.*, 2011]. A second band exists between 120°E and 180°E, but largely disappears after restraining the selection to VGPs below 45° latitude; the group of VGPs at midnorthern latitudes within the 150°–180°E sector (Figures 7f and 8a) belong to the Steens Mountain record and, therefore, bias the results (Figure 8c) toward a single record, which is not representative of a geomagnetic cluster. Note that there is also some preference of VGPs for the African longitudinal band in both selections. In summary, the existence of preferred longitudes depends on data selection and, therefore, has no stable solution yet. Such instability points to the difficulty in performing a meaningful statistical treatment of the VGP distribution within each longitudinal band. In addition, recurrent VGPs from different records within the same longitudinal band do not mean that they belong to the same time period during the reversal. To summarize, in the present state of the database, we do not see any significant indication favoring a recurring preference of VGPs within the American or Australasian longitudinal bands. We are tempted to consider that since their existence is far from being straightforward, they are most likely not a dominant characteristic of the reversing field. Regardless, the number of data points remains small.

From these considerations we infer that individual VGP paths, and their global geographical distribution suggest the existence of a rapidly varying transitional field without recurring features and no obvious preference for poles with specific longitudes. There is also no direct evidence for dominant axisymmetrical components, but obtaining many records of the same reversal remains necessary to constrain further the transitional field geometry. Given the difficulties for acquiring detailed high-quality records, this leaves little hope of documenting the harmonic content of the transitional field beyond degree 2 or 3. Note that in the present state of the volcanic database presented in Figures 7 and 8, which includes only two records of the same reversal, we are far from this objective.

4.7. Simulations Using Models of the Archeomagnetic Field

Assuming that nondipole field variations may not depend strongly on the dipole [*Le Mouël*, 1984], it is reasonable to separate arbitrarily the axial dipole from other components and to simulate a reversal of the axial dipole in the presence of a nondipole field with similar characteristics as the archeomagnetic field. This was done first using a constant nondipole field derived from the International Geomagnetic Reference Field [*Constable,* 1990, 1992; *Quidelleur and Valet,* 1996]. Then *Brown et al.* [2007] and *Valet and Plenier* [2008] took advantage of the first global archeomagnetic field models (CALSK) [*Korte and Constable,* 2005] over the past 7 ka. Several interesting observations are common to both simulations. Although 7 kyr is a short duration, it is long enough to investigate transitional fields that result from different nondipolar configurations. A key feature is the different VGP trajectories recorded at different sites. Some are longitudinally confined while others have a more complicated structure, but most are not scattered around the globe.

The longitudinal configuration of VGPs has been investigated for different field models. All simulations computed by *Brown et al.* [2007] depict some longitudinal preference, but the location of longitudinal bands differs between models. Similar conclusions were reached by *Valet and Plenier* [2008]. When results obtained for different time periods are averaged, *Brown et al.* [2007] found that preferred paths are still present but that their pattern is less marked. Similarly, transitional VGPs compiled from simulations of 10 reversals have a significant preference within the African longitudinal band. However, these preferred paths over Africa are generated from field changes that occurred during the past 7 ka and have no relationship with long-term persistent lower mantle seismic anomalies.

Simulations were also carried out to explore the effect of sediment magnetization on VGP paths [*Valet and Plenier,* 2008]. In all cases, sedimentary VGPs appear to be more longitudinally confined than the original field configuration and preferential longitudinal bands can be easily generated in the presence of a complex and rapidly varying nondipole field. This indicates that inference concerning the role of the lower mantle in VGP configurations is not exclusive and, therefore, not always relevant.

Brown et al. [2007] and *Valet and Plenier* [2008] both noticed that rapid directional changes in the presence of very low field intensities can occasionally result from geometrical effects and not from physical processes within Earth's core. These features are remisniscent of rapid directional changes reported from transitional lava flows at Steens Mountain, Oregon [*Coe and Prévot,* 1989; *Coe et al.*, 1994; *Camps et al.,* 1999].

4.8. Rapid Directional Changes During Transitions?

The reversal transition zone at Steens Mountain, which was initially discovered by *Watkins* [1965] and subsequently revisited by *Mankinen et al.* [1985] and *Prévot et al.* [1985], is the most detailed reversal record obtained so far from a volcanic sequence. It has been extended further to new sections [*Jarboe et al.,* 2011] to provide additional transitional directions. A puzzling finding is the presence of two large directional gaps while each flow preceding the gap is characterized by a distinctive evolution of paleomagnetic directions. After carefully analyzing the results, the fidelity of the record was defended in a series of papers [*Coe and Prévot,* 1989; *Coe et al.*, 1994] to indicate a rapid field evolution, which implied that the field direction changed by large amounts during the week or two required for cooling and acquisition of remanent magnetization. *Coe and Prévot* [1989] quoted directional changes as rapid as 1°/d, to contrast, for instance, with directional changes of the order of 1°/yr in the 980 B.C Levantine geomagnetic spike model of

Fournier et al. [2015]. This geomagnetic scenario has been recently retracted by *Coe et al.* [2014] after performing rapid continuous thermal demagnetization using the Triaxe vibrating magnetometer [*Le Goff and Gallet*, 2004]. It was found that all directions point toward the direction of the underlying lava flow. Long laboratory heating during thermal demagnetization would have affected the magnetic grains carrying the viscous component and, therefore, increased the unblocking temperatures of the magnetic minerals that carry the paleomagnetic signal. This scenario is currently being tested. Other possibilities such as early acquisition of a resistant chemical magnetization cannot be ruled out.

Several other studies have reported intriguing evolution of the magnetization within a single lava flow. *Hoffman* [1984] observed variable remanence directions within a transitional flow in the Oligocene Liverpool volcanics of eastern Australia. However, thermal demagnetization enabled removal of the most resistant overprint. Similarities with the Steens Mountain record can also be mentioned for several sequences of superposed lava flows that recorded the last reversal at La Palma island (Canary islands, Spain) as well as for a normal-to-reverse polarity transition of the Cobb Mountain event (1.1 Ma) in Ethiopia [*Valet et al.*, 1998]. The remanence changes direction as a function of sample height in the flow underlying the first normal (or reversed) polarity flow with a specific evolution between the two polarities. This pattern suggests that the entire reversal occurred during the time required for lava cooling from the Curie temperature, which in this case did not last longer than a few weeks and is incompatible with the rate of geomagnetic changes in Earth's core. Partial chemical remagnetization appears to be responsible for this anomalous paleomagnetic behavior, yet no complete scenario is satisfactory. These results confirm that apparent rapid changes within a volcanic unit do not reflect field changes and that particular care must be taken when sampling transitional flows.

A rapid polarity transition has recently been reported [*Sagnotti et al.,* 2014] for the last reversal from a paleolacustrine sequence from the central Apennines, Italy. In these rapidly deposited sediments, the absence of intermediate directions led the authors to suggest that the reversal duration did not exceed a few years. Continental sediments likely behave differently than marine environments and can be affected by large changes in depositional conditions. In the case of *Sagnotti et al.* [2014], it is puzzling that the deposition rate changed by a factor of 4 between the levels preceding and following the transition. As is the case for volcanics, we cannot exclude the possibility that complex mineralogy obliterated the transition. The unblocking temperatures of the samples surrounding the transition do not exceed 450°C, so that the characteristic component does not appear to be controlled by pure magnetite and suggest that either titanomagnetite or magnetic iron sulfides record the paleomagnetic signal. This may contrast with thermomagnetic results, but the latter might not involve exclusively the fraction of monodomain grains that carries the remanence. Titanomagnetite is a common magnetic iron oxide in volcanic lava flows. It is usually considered to carry an early pristine magnetization. However, the existence of rapid directional changes within transitional flows suggests that early remagnetization processes could be linked to the presence of titanomagnetite. This is also consistent with the fact that the presence of titanomagnetite is mostly incompatible with determinations of absolute paleointensity [*Valet et al.,* 2010]. A large variety of other magnetic minerals can generate long-term remanent magnetization components. Some are inherited, while others result from late chemical transformations of magnetic minerals. They can have similar distributions of relaxation times and, therefore, record overlapping magnetization components that cannot be isolated properly. We already mentioned the case of iron sulfides that occur frequently in sediments, a well-known mineral being greigite. It is important to realize that even a small concentration of a mineral that does not belong to the magnetite series can have a major impact on a reversal record. The weak magnetization of the primary component due to the weakness of the field (one tenth of its pretransitional value) considerably amplifies the importance of any secondary overprint. Components that represent one twentieth of the total magnetization are barely visible during periods of full polarity but can become as strong as the primary remanence during transitional periods and constitute spurious transitional directions. One of the best approaches for detecting overlapping components with similar spectra is through stepwise thermal demagnetization. This is difficult with soft sediments so that few studies have used this technique, except for sediment outcrops. The rapid magnetization changes in the record of *Sagnotti et al.* [2014] are not systematically detected in polarity transition records and remain partly unexplained. If we do not completely rule out any geomagnetic interpretation, reversal duration depends on the site location and likely on the local nondipole field configuration. The Apennines and the Canary Islands are not so far from each other, so some consistency might be expected between these inferred extremely rapid reversals, but certainly not over a period as short as a few weeks. Rapid VGP movements within the transition could also result from geometrical effects [*Brown et al.*, 2007] that relate to part of the transition and not to the entire reversal.

We are, thus, inclined to favor remagnetization effects as an explanation for these paleomagnetic results. Regardless, these studies provide important lessons and raises questions on the trust that we usually place on volcanic records. It is clear that we have not yet reached a complete understanding of remagnetization processes. If we extrapolate these results, we suspect that resistant overprints could also affect lava flows during periods of full polarity. In this case, spurious components preserve a direction close to that of the characteristic magnetization component and would be difficult to detect, but large enough to alter records of secular variation.

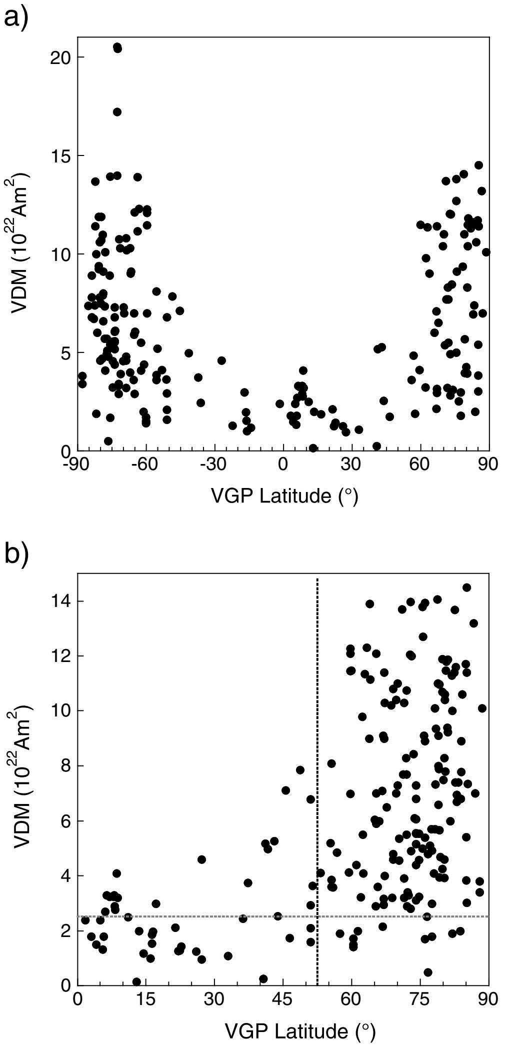


Figure 9. (a) Virtual dipole moments as a function of VGP latitude from volcanic reversal records for which absolute paleointensity determinations are available. (b) Same as Figure 9a after reversing the negative VGP latitudes.

5. Geomagnetic Intensity Across Reversals

5.1. From Paleointensity Experiments

Absolute paleointensity determinations from lava flows and records of relative paleointensity indicate a significant field intensity decrease during reversals, which in most cases can be detected from the weak magnetization of transitional samples. The large amplitude of the drop and its systematic presence rules out factors other than field intensity. In all cases, the amplitude of the decrease reaches at least 20% and frequently less than 10% of the mean field intensity during periods of stable polarity. There is some ambiguity in estimating the exact amplitude of change. For sediments, the weakest relative paleointensity value is mostly not relevant due to lack of resolution caused by the time-averaged magnetization. For the purpose of estimating paleointensity over short time periods, it is more meaningful to consider volcanics. It is useful to remember that zero or extremely low geomagnetic field intensities are unlikely because the local crustal magnetization always generates a local field.

We have selected the five polarity transition records obtained from sequences of superposed lava flows that incorporate records of absolute paleointensity using the classical *Thellier and Thellier* [1959] approach. The site distribution (Canary Islands, Hawaii, Oregon, and Iceland) is not perfect, but wide enough to avoid local biases. In Figure 9 we show the pattern of the virtual dipole moments (VDMs) as a function of VGP latitude. The plot is independent of the sense of reversal. A first observation is that most low VDMs coincide with low VGP latitudes, but some also occur at high latitudes. The field intensity value alone does not allow discrimination between a persisting dipolar geometry with a declining field that preserves a constant dipole/nondipole ratio or an increasing nondipole/dipole ratio in which the strength of the nondipole field remains unchanged. However, we have discussed above that directional results are incompatible with a dipolar transitional field, and therefore, high- and low-VGP latitudes during periods with weak fields must reflect the geometry of the local nondipole field. The coherency of this picture is supported by simulations based on the VGP distribution obtained from the present nondipole field [*Valet et al.,* 2012].

Following a first publication [*Valet and Meynadier,* 1993] several sedimentary records have been reported with a sawtooth-shaped behavior [*Meynadier et al.,* 1994; *Valet et al.,* 1994] across reversals that describe a long-term decline prior to the transition in contrast with a rapid and intense recovery after completion of the directional polarity switch. The SINT-2000 stack comprises the most detailed records published 10 years ago [*Valet et al.*, 2005] and contains evidence for an 80 kyr decay, while recovery occurred within a few kiloyears at most. Evolution of the dipole field intensity across all reversals captured in SINT-2000 is similar when records are plotted on top of each other. This suggests the existence of asymmetrical field behavior that would have significant consequences. The decay phase could result from dominant diffusion, while the recovery phase would be primarily caused by advection in the Earth's fluid outer core. This asymmetrical field intensity pattern during periods preceding and following reversals is controversial and has been discussed in several papers [e.g., *Valet,* 2003; *Tauxe and Yamazaki,* 2009]. One of the reasons that this observation has generated controversy is that the decrease is not a monotonic decline, but rather occurs as a sequence of steps, each lasting about 15 kyr. Also of interest is the suggestion that the time-averaged field intensity seems to be related to reversal frequency [*Valet et al.*, 2005]. A similar observation was reported earlier by *Constable et al.* [1998] from Oligocene sediments.

It has been suggested that an asymmetrical signal across reversals can be generated by persistent viscous effects [*Kok and Tauxe,* 1996]. However, this hypothesis requires an unrealistic distribution of relaxation times for magnetic grains that was contradicted by thermal demagnetization results at high temperatures that replicate those obtained by alternating field demagnetization [*Meynadier et al.,* 1998]. A second suggestion involves progressive postdepositional magnetization lock-in that smears the signal and generates a V-shaped profile of magnetization intensity across the reversal [*Mazaud,* 1996; *Meynadier and Valet,* 1996]. This hypothesis cannot be fully tested. Postdepositional reorientation of magnetic grains occurs and likely varies considerably for different kinds of sediments, but the consequences for paleomagnetic recording depend on the thickness of the sediment layer concerned. A 100 kyr intensity decline requires a 4 m depth for complete lock-in at a deposition rate of 4 cm/kyr. Such large lock-in depth is unlikely and would generate heavy directional smoothing.

Summarizing the list of records with and without sawtooth relative paleointensity patterns (see *Valet* [2003], *Yamazaki and Oda* [2005], and *Tauxe and Yamazaki* [2009] for reviews on the subject) would not be helpful because arguments and counterarguments can be made. After examining the geomagnetic field and its time derivative on a range of time scales, *Ziegler and Constable* [2011] reported a clear asymmetry in the statistical distributions for growth versus decay rates of dipole strength for periods longer than about 25 kyr. At a period of 36 kyr, the average growth rate is about 20% larger than the decay rate, and the field spends 54% of its time decaying but only 46% of the time growing. These differences are not limited to times when the field is reversing, which suggest that the asymmetry is controlled by fundamental physical processes that underlie all paleosecular variation. The longer decay cycle might suggest episodic periods where the field is dominated by diffusive processes, followed by transient episodes of strong axial dipole growth.

In many cases, the intensity decrease preceding a reversal is masked by a succession of fluctuations. Apart from geomagnetic modulation, we cannot neglect the fact that relative paleointensity records can be affected by subtle changes in sedimentation that result from climatic variations. The remanent magnetization and the normalizer used in relative paleointensity studies to account for changes in concentration of magnetic minerals can respond differently to changes in sedimentation, hence to the amount and nature of magnetic particles. The detailed sedimentary record from ODP Site 983 in the North Atlantic Ocean [*Channell et al.*, 2004] provides an example. A series of analyses [*Guyodo et al.,* 2000] based on comparisons of spectral contents investigated that the magnetization could be partly contaminated by climatic components. It was found that this might be the case within specific sedimentary intervals, but that the field intensity pattern was globally preserved. Notwithstanding, symmetrical paleointensity variations across the reversal recorded at this site correlate with climatic variations expressed by δ^{18}O (Figure 10a). The relationship persists after subtracting the SINT-2000 curve (Figure 10b) from the Site 983 data set. Correlation does not imply causality, but such a similarity between the two curves is unlikely to be fortuitous and suggests that paleomagnetic records can be partially shaped by factors other than field intensity.

If we return to consider volcanics, only five studies have successfully extracted absolute paleointensity results from sequences of superposed flows [*Prévot et al.,* 1985; *Bogue and Paul,* 1993; *Quidelleur and Valet,* 1996; *Herrero-Bervera and Valet,* 2005]. An absence of detailed chronologies makes it impossible to compare the durations of field decreases and recoveries during prereversal and postreversal phases, respectively

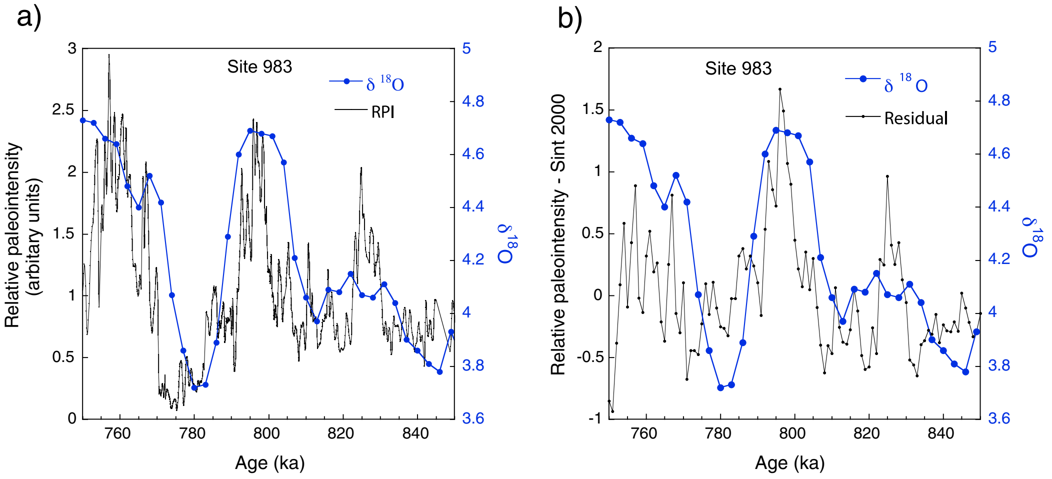


Figure 10. (a) Evolution of relative paleointensity at ODP Site 983 [*Channell et al.*, 2004] compared to changes in ™^{18}O. (b) Same as in Figure 10a after subtracting the paleointensity signal of SINT-2000 [*Valet et al.*, 2005].

[*Guyodo and Valet*, 1999]. Notwithstanding this limitation, it might be significant that all four records have lower values before than after the transition (Figure 11). This finding is compatible with features revealed by sedimentary records and supports the existence of asymmetrical prereversal and postreversal phases.

Marine magnetic anomalies can provide an alternative to relative and absolute paleointensity for determining past geomagnetic fluctuations. Ocean crust thermoremanence has long been interpreted without any direct relationhip to geomagnetic field intensity, until *Gee et al.* [2000] correlated near-sea floor magnetic anomalies of the southern East Pacific Rise with independent paleointensity estimates. The first record of geomagnetic intensity preserved in oceanic crust over the past 800 ka [*Gee et al.*, 2000] enables correlation

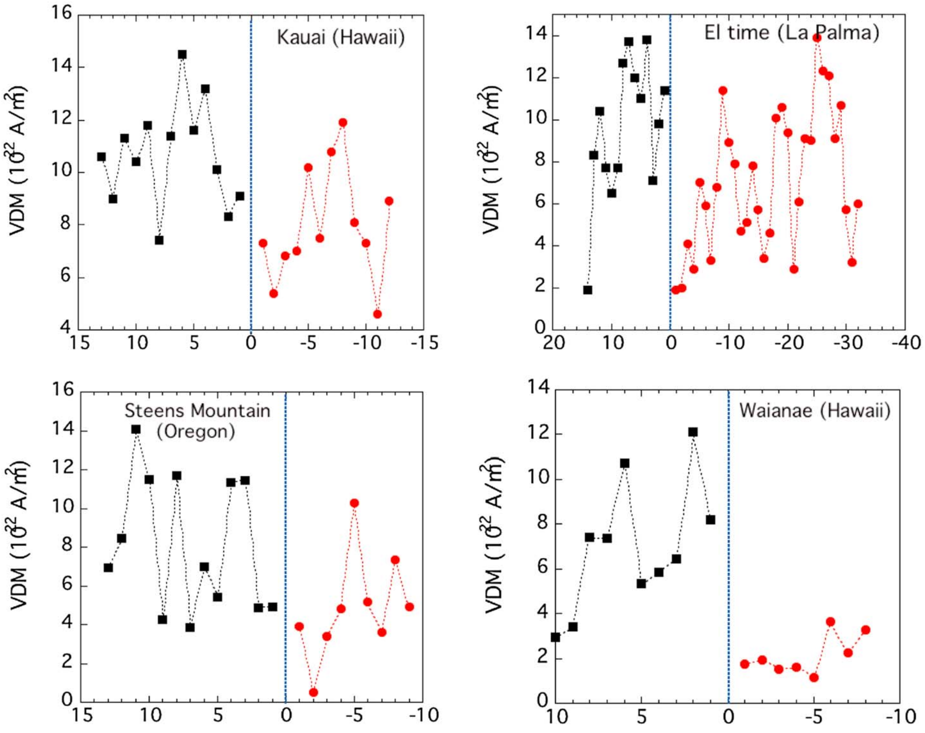


Figure 11. Changes in VDM across the four best documented polarity transition records. Vertical blue lines indicate the position of directional changes. Intensities prior to the transitions (red) have globally lower values than after (black).

with the SINT-800 composite relative paleointensity record (and by extension SINT-2000) and reveals asymmetrical variations across the last reversal.

5.2. Changes in Cosmogenic Isotope Production

Alternative markers can also document geomagnetic field intensity evolution. Changes in cosmogenic isotope production such as beryllium 10 with its long half life of 1.4 Ma, provide, in principle, an indirect estimate of geomagnetic intensity changes with time. The magnetic field lines of the dipole extend far into space, and they guide cosmic rays to the top of the atmosphere. Collisions with atmospheric constituents generate cascades of chemical reactions that yield production of cosmonuclides [*Beer et al.,* 2012]. ^{10}Be production rate is constrained by penetration of cosmic particles inside the magnetosphere and, therefore, depends on the orientation of magnetic field lines. Particle access to the atmosphere varies strongly as a function of cutoff rigidity, which is a quantitative measure of the effective geomagnetic shielding modulation. At geomagnetic latitudes higher than 65°, cosmic rays of all energies can reach Earth, while at low latitudes the field lines deflect most charged particles. As a consequence, changes in dipole intensity affect cosmogenic nuclide production at low geomagnetic latitudes, while they have no effect at high latitudes. However, this latitudinal pattern is affected by atmospheric circulation, which redistributes ^{10}Be atoms attached to aerosols and ultimately homogenizes the cosmonuclide distribution. Some equatorial production is transferred and ultimately sequestered at high latitudes so that high latitudes and polar archives are eventually also both sensitive to geomagnetic modulation.

Large ^{10}Be production rate peaks are expected during periods of weak geomagnetic field intensities and, therefore, a significant ^{10}Be production increase is expected during geomagnetic reversals. The first increase in ^{10}Be production during a transition recorded in marine sediments was reported by *Raisbeck et al.* [1985]. Convergence between relative paleointensity and ^{10}Be signals might thus provide pertinent information concerning their resolution and their respective fidelity in recording field variations. In particular, unless the ^{10}Be content within sediments is affected by factors other than the field, the asymmetrical pattern of relative paleointensity should be duplicated. *Raisbeck et al.* [1994] reported that ^{10}Be data measured across the last reversal at ODP Site 851 (which is the same sediment as in *Valet and Meynadier* [1993]) were inconsistent with the paleointensity record. However, the ^{10}Be data do not change during the reversal and, therefore, cannot be validated.

Five ^{10}Be studies have been conducted so far across the last reversal. Four records were obtained from sediments and include both radionuclides and magnetic measurements. The last record is from ice cores and, therefore, was not duplicated by any record of relative paleointensity. The first data set is from core MD97-2143 [*Carcaillet et al.,* 2004] from the North of New Guinea (02.03°N; 141. 46°E) and spans the 600–1300 ka interval (Figure 12a). The ^{10}Be/^{9}Be ratio is asymmetrical across the M-B transition. In contrast, results from core MD05-2930 [*Ménabréaz et al.*, 2014] in the Papouasia Gulf (10.25°S, 146.25°E) have a large symmetrical peak during the transition, as is the case for core MD90-961 [*Valet et al.,* 2014] from near the Maldives (eastern Equatorial Indian Ocean). The study conducted on three cores from the western Equatorial Pacific [*Suganuma et al.,* 2011], which are also from the same area (1.87°S–166.88°W; 4,27°N–134.82°E; 15.87°N–124.65°E), was restrained to the interval surrounding the last reversal. Only the ^{10}Be results from core MD97-2143 increase significantly during the M-B transition, while changes in production should not be different among the three cores. These discrepancies are likely due to the absence of normalization of ^{10}Be changes with respect to the variations in ^{9}Be which allow compensation for local production changes resulting from ^{10}Be scavenging effects or from local changes in particles deposition. We, thus, select only the three records with large ^{10}Be changes concomitant with the last reversal and compare these sedimentary data with the ^{10}Be record from the Epica Dome C ice core [*Raisbeck et al.*, 2006]. The ^{10}Be data sets are plotted in Figure 12b on their respective time scales and are normalized to their mean value. The vertical axis of ^{10}Be production is reversed in order to compare directly ^{10}Be changes with field intensity changes revealed by the composite SINT-2000 record. The time scale of SINT-2000 has been moved by 5 kyr to match with the recent time scales used for the ^{10}Be records. Similarly, the same results are plotted in Figure 12c along with the PISO stack that is biased to the northern Atlantic Ocean [*Channell et al.,* 2009].

The four ^{10}Be peaks have a similar bell-shaped pattern that culminates at about 770 ka (Figure 12a). However, the overall shape of ^{10}Be production changes does not always match the corresponding relative paleointensity

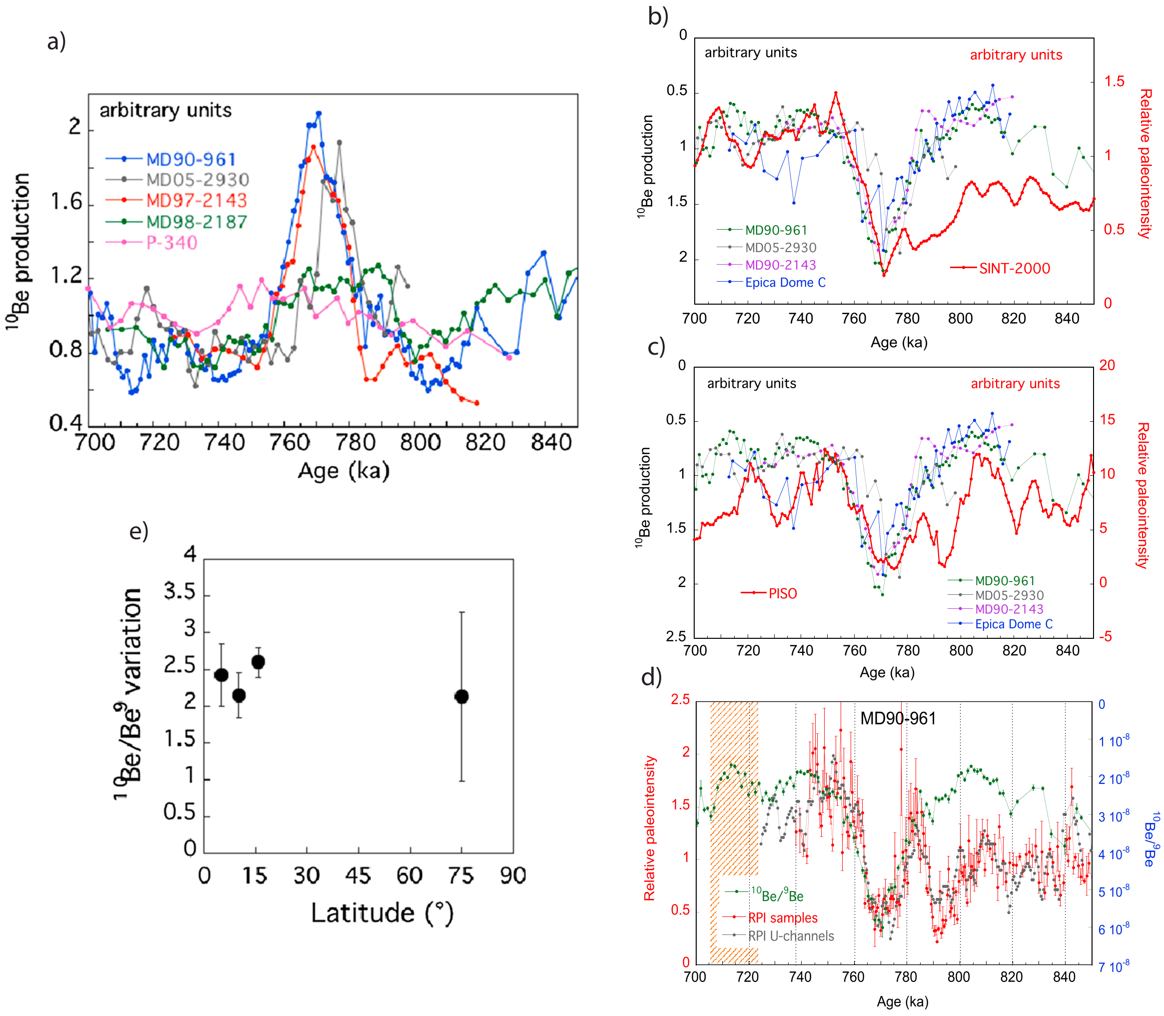


Figure 12. (a) Evolution of ^{10}Be production as a function of age across the last reversal for the five records obtained so far. The three ^{10}Be peaks are coeval with the reversal and culminate at the same level. Inverse of ^{10}Be changes as a function of time compared to the (b) SINT-2000 and (c) PISO curves. (d) Relative paleointensity and inverse of ^{10}Be changes from core MD95-961 as a function of time across the last reversal. Note the divergence between ^{10}Be production and paleointensity changes in all three cases. (e) Changes in amplitude of ^{10}Be peaks as a function of site latitude.

records. This is clear for the intervals that precede the transition of both composite records (SINT-2000 and PISO) and also during the period following the reversal in PISO (Figures 12b and 12c). If we compare ^{10}Be changes and relative paleointensity in the high-resolution record from core MD90 961 (Figure 12d) we observe the same discrepancy. Postdepositional reorientation of magnetic grains could be the cause, but then there should exist a large difference when comparing with PISO and SINT-2000 as their resolution differs by almost a factor of 10. This is not the case and, therefore, fluctuations in both curves at the same time are difficult to reconcile with this hypothesis. In addition, this scenario would not explain the differences after the reversal. Other possibilities can be raised such as the existence of a threshold in the response of ^{10}Be production. New detailed records will help to clarify these aspects.

In order to compare quantitatively the amplitudes of ^{10}Be changes among the four data sets, the peak value of each record is divided by the corresponding mean value of the baseline outside the reversal zone. We rely on the standard deviation of the baseline variation to estimate the uncertainty of the results. It is striking in Figure 12e that all records have the same amplitude, which means that the same production changes are recorded simultaneously at all sites and, therefore, that there is no apparent latitudinal dependency. Additional variability present in the EPICA record could reflect larger field fluctuations at these high latitudes. Overall, the global similarity of the four records indicates that the same amount of ^{10}Be has entered the sediment and the ice between the equator and the pole. Even if we assume complex multipolar transitional field geometry, the homogeneous distribution of ^{10}Be production between these latitudes is certainly not possible without large atmospheric mixing.

Summarizing, paleointensity indicators are mostly consistent with each other and confirm an overall systematic intensity drop accompanying reversals. The value of the lowest intensity field reached during the transition remains relatively poorly constrained, and different indicators do not always provide the same pattern of variations. Future progress will depend on our ability to understand further the signals inherent to independent proxies such as relative paleointensity and ^{10}Be production. Parallel records of both indicators using the same samples would be a significant step in this direction.

6. Dynamics of Reversals

6.1. Precursors and Rebounds

We have discussed that relative paleointensity records contain pronounced oscillations prior to reversals. These variations drew the attention of *Hartl and Tauxe* [1996] who studied several cores with relatively low deposition rates across the last reversal. They confirmed that an initial intensity drop prior to the polarity change characterizes most relative paleointensity records and interpreted this event as a precursor of the transition. The occurrence of intensity minima, sometimes of a double dip, prior to reversals has been confirmed in subsequent detailed records of relative paleointensity [*Channell et al.,* 2004].

It is reasonable to expect that these periods of low field intensity should be associated with significant directional changes provided that the nondipole components do not decrease as much as the axial dipole. However, the existence of transitional directions depends on the field geometry at the site. More than 50% of locations would not experience any directional change if the historical field is reduced to 10% of its value during the past three millennia [*Valet et al.,* 2012]. Also, sedimentary records can be affected by significant time averaging. Based on thermal demagnetization results that were more efficient in removing viscous components, *Hartl and Tauxe* [1996] emphasized the role of viscous overprinting and minimized the influence of postdepositional particle realignment. Testing between these options is difficult because none of these processes is systematic and both could be present. Provided that there is a linear decay toward the origin of demagnetization diagrams, it is difficult to imagine that large viscous components have not been removed properly. High coercivity components linked to minerals other than magnetite mostly do not carry a primary characteristic magnetization component.

Volcanic records from piled lavas also reveal the dynamical structure of reversals. Volcanic records from superposed flows have been correlated with each other by anchoring them to the lower and the upper boundaries of the transition between two polarities [*Valet et al.,* 2012]. A single multiplicative factor can be used to match time scales. Unexpectedly, all records correlate nicely and three successive phases of the reversal process are indicated with a precursor, a 180° switch, and a rebound (Figure 13a). The first and last events are likely constrained by the geometry of the local nondipole field and therefore are not always observed. They can be associated with the typical characteristic times of secular variation. The assumption inherent to constructing the sequence is that the numbers given to successive directions are related linearly with time. Therefore, the duration of each event is evaluated by reference to the characteristic times for secular variation of the nondipole field. The first and third phases are estimated to have lasted less than 2.5 kyr, while the directional polarity transition did not exceed 1 kyr.

As discussed above, the same structure should be present in sediments provided that the temporal resolution is appropriate. Taking advantage of the database of the last reversal (see section 3.2), we attempted the same approach as for volcanics. The match is again successful (Figure 13b), but only the high-resolution records from the North Atlantic Ocean [*Channell et al.,* 2004] and Boso Peninsula [*Niitsuma,* 1971] have a complex dynamical structure, which confirms the role played by the time-averaging process for lower resolution records. The same smoothing has been argued to apply to the geomagnetic excursions [*Roberts and Winklhofer,* 2004]. Few transitional directions have been reported during the excursions that punctuated the Brunhes and Matuyama polarity intervals except in high-resolution records.

It is important to discern whether the precursor and the rebound are linked directly to the reversal process or whether they are far enough apart to be considered independent events. Addressing this question requires

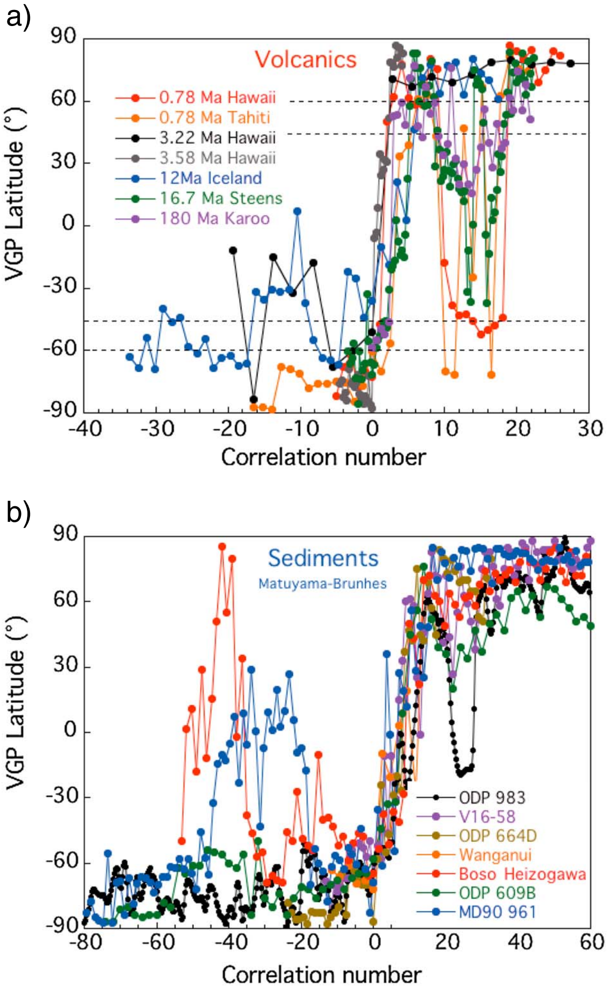


Figure 13. (a) Stratigraphic variation of VGP latitude obtained after matching the first and last transitional directions of each volcanic reversal record and interpolating linearly between. All the numbers defining a sequence have been multiplied accordingly by a single factor that represents the ratio of transitional lava flows between this sequence and the Maui record. This is equivalent to tuning all records to a common duration. (b) Same for the sedimentary records of the last reversal from the database defined in section 3.2 (bottom) with reference to the stratigraphy thickness.

good knowledge of the chronology of successive events. The challenge is difficult since most current dating techniques do not provide resolution better than a few kiloyears for the last reversal. In addition, the ages do not always involve exactly the same period during the reversal. They can either be obtained from transitional lava flows or from flows immediately below or above and thus be separated by different time intervals. Therefore, we cannot exclude that the stratigraphic position of the flow used for dating generates inaccuracies, which is not without consequences for estimating the durations of successive phases and even for the age of the reversal itself. Dating the last reversal with precision has captured much attention since this event provides the best opportunity for comparing different techniques and calibrations. Recent compilations [*Singer et al.,* 2005; *Channell et al.*, 2010; *Valet et al.,* 2014] indicate that the precursor occurred at 790 ± 5 ka, while the midpoint of the transition occurred at 773 ± 5 ka [*Channell et al.,* 2010; *Valet et al.*, 2014]. The age of the onset of the transition varies depending on the records but does not seem to be older than 778 ± 5 ka. The 5 kyr uncertainty is justified by the fact that any astronomically tuned age for this period cannot be defined better than within ±5 kyr. By comparison with the long-term evolution of historical and archeological secular variation, the duration of the precursor would not exceed 2.5 kyr [*Valet et al.*, 2012], which yields an estimate of about 10 kyr for the following period that was likely associated with a small field intensity recovery, keeping in mind that it could have been as short as a few kiloyears.

A question that comes to mind is whether it is pertinent to determine the field geometry when reversals appear to be characterized by a succession of events that could be driven by different mechanisms. Assuming that the precursor and rebound can be regarded as large-amplitude secular variation in the presence of a weak dipole, one may wonder whether there are significant differences with the transition between the two polarities, which is short and not so well defined in many records. Despite the relatively small number of data, the VGP distribution inherent to the transition does not differ strikingly from the data that incorporate the three phases in Figures 7 and 8. It provides an image of a complex nondipole field that varies with amplitude and characteristic times that appear to be similar to those of the present nondipole field.

6.2. From Past to Future: Precursors for the Next Reversal?

The Brunhes chron has been unusually long with respect to the past 10 Ma, with an average of one reversal every 200 kyr. Is a reversal overdue? Based on the decreased dipole strength during the past 800 years and its relationship with growing patches of reverse flux (at the CMB) in the South Atlantic Ocean, it has been proposed [*Bloxham and Gubbins,* 1986; *Gubbins and Coe,* 1993; *Hulot et al.,* 2002] that the field is in a configuration that could possibly lead to a reversal in the relatively near future. The appearance and subsequent growth of reverse flux patches is a feature common to most numerically simulated reversals. They reflect the emergence of multipolar magnetic upwellings [*Aubert et al.*, 2008] followed by reverse flux expulsion at the CMB (see *Amit et al.* [2010] for a review on the topic, and the detailed description of a simulated reversal by *Olson et al.* [2011]). These features are necessary but not sufficient for a reversal to occur (because they may simply lead to an excursion, a phenomenon 10 times more frequent than a reversal in the best documented past 800 ka). With respect to the present-day situation, we have insufficient detailed information from the historical and archeomagnetic field to constrain the lifetime of a reverse flux patch such as the present South Atlantic flux patch. Despite enormous progress in constructing archeomagnetic databases and models [e.g., *Korte et al.*, 2011; *Licht et al.*, 2013], we have not reached the resolution that enables detection of the persistence, growth, or decay of reverse flux patches at the CMB. If we refer to the decline of the dipole through time, there are many examples of long dipole decreases in the paleomagnetic record that did not end with a reversal. Moreover, despite its present evolution the present dipole remains strong ($\sim 8 \times 10^{22}$ A m^2) and, thus, far from values that preceded the past five reversals ($< \sim 4 \times 10^{22}$ A m^2). The present evolution falls within the normal range of field variability that prevailed for the past 2 Ma (see the more detailed statistical analysis by *Constable and Korte* [2006]).

Prediction of temporal geomagnetic field variations can in principle be achieved by data assimilation, whereby dynamical geomagnetic field models are combined with observations of its variability [*Fournier et al.,* 2010]. The forecast horizon of such ventures is intrinsically bounded by the limited predictability of the geodynamo, which is estimated to be on the order of a few decades to a century [*Hulot et al.,* 2010; *Lhuillier et al.,* 2011b], based on the study of so-called error growth in a suite of numerical dynamo models. This predictability limit is at least 1 order of magnitude smaller than the time it takes for a reversal to occur. This leaves in principle little hope for predicting the next reversal. Nevertheless, reversals are peculiar features of geodynamo variability, and their dynamics may be described using physics with longer characteristic time scales (hence increased predictability) and less complexity than the one at work behind full secular variation. The physics could for instance take the form of low-dimensional models, such as those proposed by *Pétrélis et al.* [2009] and *Gissinger* [2012]. This conjecture remains to be tested in light of available paleomagnetic data.

6.3. Is There Anything to Learn From the Sun?

The only other active magnetic dynamo in the solar system that provides direct evidence of polarity reversals is the solar dynamo, whose quasi-periodic 11 year cyclicity is punctuated by reversals of the axial dipole. One may, therefore, wonder whether analysis of geomagnetic reversals could benefit from analysis of solar reversals (and vice versa). Interestingly, the transitional field geometry during recent solar reversals is well constrained. *DeRosa et al.* [2012] analyzed solar magnetograms for the past three solar cycles (from 1976 to 2012). They expanded the magnetic field at the solar surface up to spherical harmonic degree 60 for Wilcox Solar Observatory data [*Scherrer et al.*, 1977] and even up to spherical harmonic degree 192 for Michelson Doppler Imager data [*Scherrer et al.*, 1977], those truncations being made possible by the fact that we have an almost direct view of the Sun. Solar reversals are found to occur at or near times of maximum activity, following a mechanism that can be explained kinematically by advection of magnetic flux at the Sun's surface. The polarity transition (defined by *DeRosa et al.* [2012] as when the dipole latitude is below 45°) lasts for 1 to 1.5 years, i.e., roughly a tenth of the cycle. The axial dipole decrease is partly offset by the increased equatorial dipole. It is noteworthy that quadrupolar energy exceeds dipolar energy during a reversal. *DeRosa et al.* [2012] further examined the behavior of the axial dipole magnitude before and after a reversal, in order to detect possible asymmetry in the decay and regrowth time (seeking a sawtooth pattern as discussed in the terrestrial case in section 5), in addition to a possible overshoot. The evidence (based on three events) is not systematic: only one event (the reversal of solar cycle 22) has an overshoot, whereas the decay and growth appear to follow equal rates (their Figure 13). These high-quality solar observations can be interpreted in the framework of dynamo theory, or using low-dimensional models such as those discussed above; see also *Pipin et al.* [2014] for an attempt at this exercise.

There are admittedly substantial differences between the solar dynamo and the geodynamo: most of the solar magnetic energy is small scale (contained in active regions), whereas the Earth's field is dipole dominated. As far as reversals are concerned, the Sun undergoes quasi-periodic polarity reversals and no excursions, unlike Earth, where reversals are irregular and excursions more frequent. Despite these differences, it seems sensible to think that each community should benefit from cross fertilization of conceptual models when interpreting observations, particularly those that characterize the transitional field.

7. Summary

We have reviewed and discussed prominent features that have been reported from paleomagnetic records of field reversals and their compatibility with ideas drawn from idealized numerical dynamo simulations. Keeping in mind that future progress or new findings can bring new views, we can estimate the degree of confidence that, to our eyes, can be assigned to them. The following provides a summary of the various matters discussed.

1. Large and systematic field intensity decreases occur during all-polarity transitions. There are no documented transitional directions with strong magnetization intensity during reversals, unless they have undergone remagnetization. The existence of a weak dipole can be considered a robust feature and could announce the arrival of a reversal. Large geomagnetic excursions, specifically those that have been identified during the Brunhes and Matuyama periods, are also characterized by low field intensities. Excursions have not been discussed in the present paper, which is focused on reversals, but an extensive review is provided by *Laj and Channell* [2015]. We mention here simply that in the best documented excursion records [*Channell*, 2006; *Roberts,* 2008], the field reversed for a short period of time before returning to the original polarity. It would be helpful to determine whether the field reached the same low intensity during these aborted reversals as during the full reversals. Detailed studies of ^{10}Be production are appropriate to provide additional clues on this matter [*Ménabréaz et al.*, 2012]. Absolute paleointensity from volcanics could help, but it is challenging to find lava flows that erupted during the short period when the field was weakest.
2. There are strong indications that the geomagnetic field was not dipolar during the last reversal. Less evidence is available for the other reversals due to the absence of multiple contemporaneous records of the same reversal. However, it is reasonable to consider that the same causes produced the same effects and, therefore, the systematic presence of a weak transitional field must be regarded as the most direct consequence of dipole decay. Evidence for a nondipolar transition is reinforced by the complexity of VGP paths derived from the most detailed volcanic records. It is also supported by the apparent relationship between site latitude and reversal duration indicated by sedimentary paleomagnetic records.
3. A major debate has concerned the existence of preferred longitudinal bands of transitional VGPs and their relationship with convective patterns in Earth's lower mantle. Debate was initiated by the observation that recording sites lie systematically 90° away from the preferred bands and that low-resolution sedimentary records (with deposition rates lower than 4 cm/kyr) confine the VGPs away from the sampling site longitude. We selected all sedimentary records of the last reversal from an updated database and did not observe any accumulation of VGPs within the two hypothesized preferred bands. The same conclusion is reached for detailed reversal records from superposed lava flows sequences. Debate continues in the absence of consensus regarding the requirements for records to be suitable for inclusion in the global databases. One way to improve the situation could be to concentrate on the last reversal.
4. The existence of recurring VGP clusters in some volcanic data and their possible relationship with lower mantle structures remain controversial. Their presence is not systematic and is restricted to some records. Series of successive eruptions are common and are well documented in most volcanic edifices. It is, thus, logical to use knowledge of volcanism, which occurs in alternating effusive and quiescent periods, rather than to invoke a more speculative geomagnetic origin. VGP clusters are present in most individual volcanic records. However, we observe no reproducible pattern of clusters between parallel sections. Regardless, we cannot refute completely a geomagnetic origin provided that the same spot would emerge in different reversals of different ages and/or if there is evidence for some relationship with intense flux patches. We notice that an Australasian VGP cluster is seen in a few records. We infer that there is no statistical meaning behind this observation. Whatsoever, this point merits consideration and should be targeted as an important objective to resolve in future studies.
5. Transitional field geometries remain poorly constrained despite several attempts to compile and model data for the last reversal. The different resolution of each record and the absence of a common age model hampers proper description of the transitional field. Another important issue is the existence of successive phases in a reversal that can induce confusion when attempting to correlate records from remote

geographical locations. Considering the complex pattern observed for the most detailed volcanic records, there is little hope of reaching a description of the harmonic content of transitional field beyond degree 3. This does not, however, reduce the crucial need for additional detailed records, particularly from volcanic sequences.

6. The complex dynamical structure of reversals is supported by sedimentary and volcanic records. Provided that resolution is adequate, the reversal process seems to incorporate one precursor and one rebound prior to and after the transition. However, the three phases are rarely observed in a single record. This is likely to be caused both by field geometry and recording limitations. The duration of each phase does not exceed 3–4 kyr. Therefore, precursors and rebounds can be seen as part of the whole process, and the expression of a continuum of behavior between secular variation, excursions, and reversals. Another possibility is that the dipole collapse is not large enough or that the nondipole/dipole ratio varies. Here again, as for other features related to field intensity, records of cosmogenic radionuclide production should help to constrain the relationship between field geometry and the existence of precursors and rebounds.
7. The existence of rapid field changes during transitional periods has proven to be a challenge for both experimentalists and theoreticians. It is now clearer that such variations are likely generated by complex remagnetizations that require detailed rock magnetic studies to identify, although the exact processes have yet to be described and likely different in each case. This finding is unlikely to be an isolated observation. It has important potential consequences for all paleomagnetic studies of lava flows and raises questions about our usual confidence in these records. Such remagnetizations are more easily detected during reversal periods, provided that there is adequate sampling across the entire thickness of lava flows. There are at least four reversal studies where such issues have been reported. It is, thus, recommended that future studies of lava flows consider this and concentrate sampling over the total thickness of lava flows.
8. A sawtoothed pattern of field intensity across reversals is not always present in sedimentary records. Controversy exists about this feature due to difficulties in estimating the amplitudes of variations that depend on factors other than field intensity. Moreover, the complexity of the field decay phase depicted by a succession of oscillations makes it difficult to observe an overall decreasing trend. It is, thus, fair to consider that this observation has not yet been fully validated and that progress on this matter will depend on the capacity to isolate contributions of factors other than field intensity. Several independent observations indicate a sawtooth-like presence of a lower time-averaged field prior to that after transitions in the volcanic data set. It is also consistent with a systematic asymmetry in the distributions of growth versus decay rates of the dipole field strength in sediments and thus is not related solely to reversals. Therefore, the field collapse that leads either to reversals or to periods of enhanced secular variation would appear to be caused by similar processes within Earth's core, which are connected to the emergence, diffusion, and transport of reverse flux patches at the CMB.

8. Outlook

Despite many unresolved questions we are far from pessimistic and consider the quest for a proper description of polarity transitions to not be hopeless. Sediments lack resolution and volcanics fail to provide detailed and continuous records. However, this statement relies on conventional paleomagnetic techniques and data treatment that have been used so far. The interest for sediments was first justified by the possibility of acquiring continuous records. Provided that resolution problems can be improved, sediments remain the most appropriate material to study reversals. What is needed is to gain in resolution by at least a factor of 10. This requires reducing sample thicknesses to millimeter sizes and to measure thin sediment slices by taking advantage of new technologies. Such sample preparation would be delicate and time consuming, but is feasible, even with soft sediments. Over the last four decades superconducting quantum interference device (SQUID) magnetometers have been used in most paleomagnetic and rock magnetic laboratories which enable measurement of the net magnetization of bulk samples (1 to 11 cm^3), while microscale measurements remained unattainable. A new generation of high-sensitivity SQUID microscopes appeared a decade ago [*Baudenbacher et al.*, 2003]. Instead of measuring the net sample magnetization, they generate a high-resolution map of the vertical component of the magnetic field ~80 to 200 μm above the sample. The magnetic scan is performed using thin sediment slices and maps the magnetization at submillimeter scale [*Lima and Weiss,* 2009]. It has been shown [*Weiss et al.*, 2007] that the bulk moment magnitude and the direction of magnetization inferred from inversions of SQUID microscopy data match direct measurements on the same samples using moment magnetometry. Magnetic scanning can be repeated at successive demagnetization steps to assess the magnetic stability at submillimeter scale and, therefore, to constrain its origin. This novel technique has enormous potential and is a promising avenue for future high-resolution studies. Assuming that significant progress will emerge from such technical developments, interest in volcanic records would become more limited. Notwithstanding, they provide accurate measurements of the total field and determinations of absolute paleointensity that are necessary to calibrate sedimentary records. The amplitude and timing of field intensity variations, particularly of the axial dipole, constrain the occurrence of reversals and excursions. We emphasize the importance of using multiple proxies. Multiple techniques for absolute paleointensity determinations now exist, but they seem to increase the dispersion of the results without increasing confidence in their reliability. We adopt a conservative approach based on the original rock magnetic principle of paleointensity determination [*Thellier and Thellier*, 1959] and argue that only noninteracting single-domain magnetite provides correct field intensity determinations. Relative paleointensity determinations have been extremely successful. We now need to resolve small-amplitude changes to clarify the origin of differences between parallel records. Apart from promising developments generated by scanning magnetometer techniques, combining ^{10}Be production records with relative paleointensity data from the same specimens will be important in future studies.

Finally, further progress in transitional field modeling should also be sought along the lines proposed by *Leonhardt and Fabian* [2007] for the last reversal. The authors supplied prior information in order to regularize their solution: they added a constraint that would tend to minimize the power required for the reversal to occur. This implied, as usual, the arbitrary tuning of a tradeoff parameter between goodness of fit and model complexity. As more data of better quality become available in the near future, and better dynamic models of reversals come to the fore, it may be timely to reconsider this approach, by supplying prior information based on the statistics of simulated reversals, with no need for a tuning parameter. The question will then be as follows: is that prior information compatible with observations, given their age and measurement uncertainties? If solving the inverse problem at hand provides a positive answer, analysis of the mechanisms at work during a simulated reversal will be worth pursuing. If, on the contrary, the answer is negative, the candidate dynamo model will be rejected and its genitor sent back to the drawing board.

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