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Correlation of paleointensity variation records in the Brunhes/Matuyama polarity transition interval

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Abstract

Paleomagnetic records of the 0.78 Ma Brunhes/Matuyama (B/M) polarity reversal interval described from high resolution (8–11 cm/kyr) deep-sea sediments from western equatorial Pacific ODP Sites 767B and 769A show two successive and marked decreases in paleointensity, of about 15 kyr wavelength each, and a shift from full reversed to full normal polarity directions in only ~ 2 kyr, associated with the uppermost paleointensity decrease. In contrast, transition records from deep-sea sediments with lower sedimentation rates tend to show simpler paleointensity variation with more complex patterns of directional change; for example, the B/M transition record described from deep-sea sediment core V16-58 from the southern Indian Ocean. We suggest that the twin ^{10}Be peaks reported in V16-58 correspond to increased production of this cosmogenic isotope, associated with the double paleointensity dips recorded in ODP 767B/769A. The low-resolution V16-58 paleomagnetic record can be accounted for by modeling of the geomagnetic field history in ODP 767B at a nominal recording rate of 1 cm/kyr and using an exponential lock-in process filter with a half fixing depth of 16 cm. The double paleointensity dips become a single, broad magnetization low and the change in paleomagnetic directions is offset by about 16 cm below the actual level of the polarity transition, similar to what we infer for V16-58. The low resultant magnetizations will be especially prone to overprinting, which, if in the present field, will tend to give an Americas VGP path. The main features of the ^{10}Be profile will be unaffected by the remanence lock-in process and, consequently, retain their usefulness for correlation as a proxy of geomagnetic dipole intensity variation.

Records of geomagnetic polarity transitions are intrinsically difficult to obtain and their reliability is often uncertain, due to the brevity (~ 10 kyr) of the polarity reversal phenomenon and the distinct possibility that subtle biases or artifacts influence the relatively weak magnetizations that typify polarity transitions. Thus, for example, the statistical significance of the tendency of transitional directions to describe longitudinally confined virtual geomagnetic pole (VGP) paths preferentially through the Americas [1,2] remains unresolved [3–5]. It is axiomatic that a broader geographic distribution of reliable transition records is needed but detailed correlation of available records from distant sites can already provide a useful framework for differentiating features, due to the reversing geomagnetic field from artifacts of the recording process.

Such detailed correlation was demonstrated in a study of the interval around the Brunhes/

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Matuyama (B/M) boundary in deep-sea sediments with high sedimentation rates from ODP Sites 767B (4.8°N, 123.5°E) and 769A (8.8°N, 121.3°E). As documented in Schneider et al. [6], the magnetizations of these sediments are strong, stable and recorded at high sedimentation rates (8 cm/kyr in ODP 767B, 11 cm/kyr in ODP 769A). A very well defined and rich microtektite horizon, representing a single, virtually instantaneous, depositional event, is present just below the B/M transition at each site and allows precise correlation between these widely separated (~ 500 km) sections from separate basins for verification of paleomagnetic features. The microtektite horizon in ODP 769A occurs within a zone of oxygen isotopic variation associated with glacial Stage 20, while the reversal in paleomagnetic directions marking the B/M boundary occurs about 1 m (~ 11 kyr) above, in the succeeding interglacial Stage 19, in excellent agreement with the sequence and timing of these events determined from independent analysis of different cores [7].

Normalized by sedimentation rate and corre-

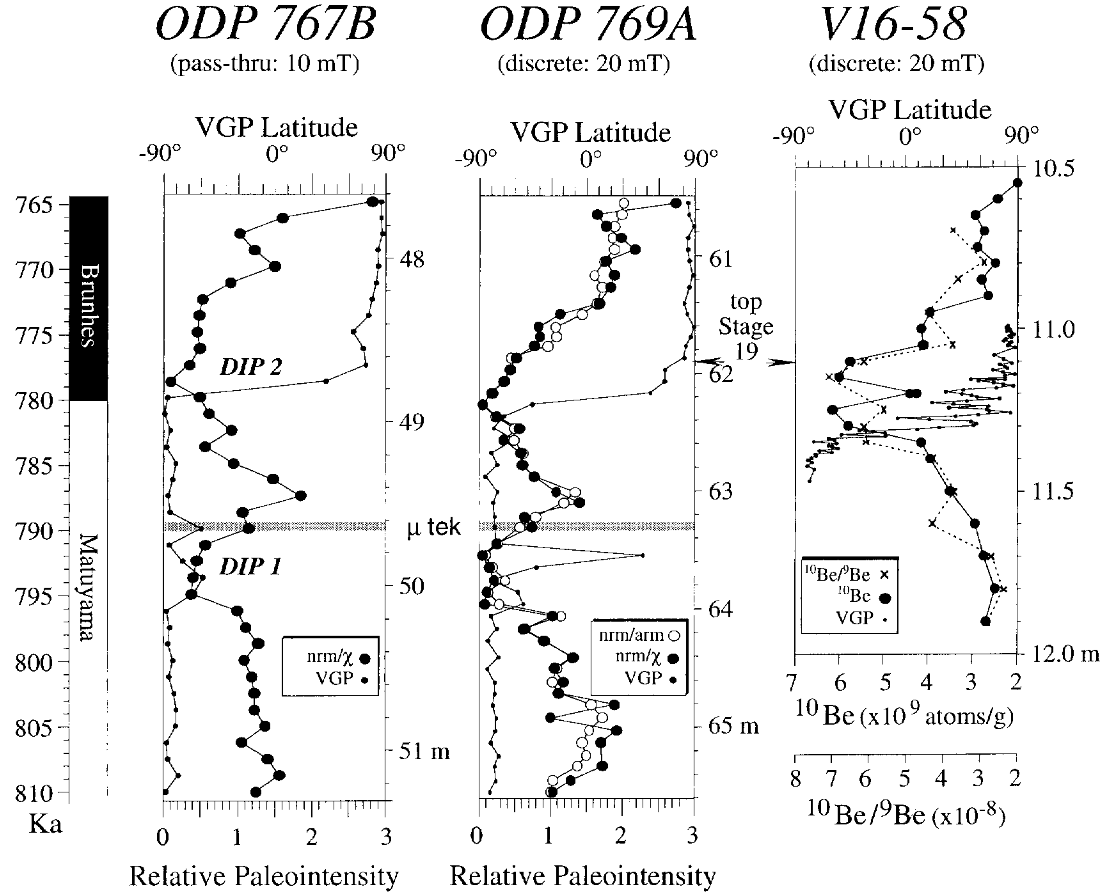


Fig. 1. Brunhes/Matuyama polarity transition records from deep-sea sediments in ODP 767B and ODP 769A [6] and V16-58 [10]. Profiles of VGP latitude and relative paleointensity (^{10}Be and ^{10}Be/^{9}Be paleointensity proxy for V16-58 [14]) are plotted at a common time scale based on published sedimentation rate estimates of 8 cm/kyr and 11 cm/kyr for ODP 767B and ODP 769A, respectively [16], 4 cm/kyr for V16-58 [10] and an age of 780 Ka for the Brunhes/Matuyama boundary [35]. The Australasian microtektite horizon in ODP 767B and ODP 769A [6], shown by stippled bands labeled μ tek, and the top of climate Stage 19 for ODP 769A [6,15] and V16-58 [10,16], indicated by arrows, were used for between-site stratigraphic correlation.

lated by the microtektite horizon, the paleomagnetic records in ODP Sites 767B and 769A, from either discrete sample or pass-through magnetometer measurements, show virtually the same chronology of geomagnetic field behavior in the vicinity of the B/M polarity reversal (Fig. 1). Of particular significance is the presence of two successive and marked decreases in paleointensity (DIP), each of similar wavelength and amplitude, based on either ARM or susceptibility normalization of the stable natural remanent magnetization. The reversal in polarity is associated with the mid-point of the uppermost paleointensity decrease (DIP 2) and is characterized by a shift in directions from those corresponding to full reversed polarity (high southern VGP latitudes) to full normal polarity (high northern VGP latitudes) in only ~2 kyr with few intermediate directions. The preceding DIP 1 is generally characterized by full reversed polarity directions. A thin zone of anomalous directions occurs at the lowest paleointensities of DIP 1 in ODP 769A; the anomalous directions are not replicated in either discrete sample or pass-through magnetometer measurements in ODP 767B and, thus, are unlikely to be a record of geomagnetic field behaviour. The microtektite horizon is located precisely in the upper part of DIP 1 at both sites, which, with other points of site-to-site correlation, indicate that the sections in ODP 767B and 769A are very likely to be complete.

DIP 2 is most probably the feature commonly interpreted as associated with the reversing field at the B/M boundary. If DIP 1 were also included as part of the transitional field behaviour, it would imply a total duration for the geomagnetic reversal process of something like 30 kyr. This would be difficult to reconcile with the existence of short, full polarity intervals (e.g., Cobb Mt., at ~25 kyr [8]) which could not reasonably be bounded by transitions of such long duration. DIP 2 alone, with a nominal duration of 15 kyr, is clearly much more consistent with previous estimates for the duration of a polarity transition. We therefore regard DIP 1 as an independent geomagnetic feature that preceded the B/M transition.

The substantial decreases in relative paleointensity by well over a factor of 2 associated with DIP 1 and DIP 2 must be due to fluctuations in the strength of the dipole component of the geomagnetic field. A similar double DIP is clearly evident in at least the highest resolution record (Hole 851D from the eastern equatorial Pacific) of a limited data set interpreted as providing the best estimate of relative paleointensities across the B/M boundary [9], supporting the global nature and dipolar origin of these paleointensity variations. The dipole field nevertheless retained a near-axial alignment over most of the interval, as evidenced by the high VGP latitudes, with only a few transitional directions within DIP 2 confined to the lowest paleointensities. The polarity transition, therefore, cannot be attributed to rotation of the dipole alone. Indeed, such a simple model of the polarity transition would be expected to produce a progressive change in VGP latitudes, corresponding to a paleointensity variation of no more than a factor of 2, which, from the vantage of a near-equatorial site,, would, moreover, be expected to show a general increase during the transition.

The ODP 767B/769A records of the B/M transition interval are thus characterized by a simple, step-like inversion of field directions and a more complex evolution of paleointensity variation. In contrast, transition records of the B/M reversal from deep-sea sediments with lower sedimentation rates tend to show more complex patterns of directional change, although there is usually insufficient detailed stratigraphic coverage to characterize the paleointensity variation that may be correlated to DIP 1. This occurs, for example, in the record of the B/M transition in deep-sea sediment core V16-58 from the southern Indian Ocean [10]. We examine this published record of the B/M transition from a southern hemisphere site (46.5°S, 31.3°E) because it has an extended stratigraphic record of the concentration of ^{10}Be, which serves as an independent proxy for dipole field intensity, and because the stratigraphy can be correlated to that of ODP 767B/769A by paleoclimatic records.

The global production of cosmogenic isotopes is inversely related to the intensity of the geomagnetic dipole field and is expected to be enhanced approximately two-fold over today's rate for the extreme null-field case [11]. The long half-life of ^{10}Be (1.5 m.y.) [12] makes this cosmogenic isotope well suited for determining its relationship to long-term paleointensity variations (e.g., [13]), especially across polarity transitions. Although mixing and variable dilution by biogenic components may have modified the concentration profile of ^{10}Be in V16-58, Raisbeck et al. [14] observed that the ^{10}Be curve was essentially the same as ^{10}Be normalized by the stable isotope ^{9}Be (Fig. 1). This suggested that the observed overall increase in ^{10}Be across the B/M transition was due primarily to an increase in production broadly associated with expected low geomagnetic field intensities during the polarity reversal. Within the interval that showed an overall increase in ^{10}Be, however, there is a prominent ^{10}Be minimum (at 1120 cm) which was replicated and confirmed. Unfortunately, no material remained from this sample for ^{9}Be determination. Considering that ^{10}Be/^{9}Be is not necessarily a better monitor of

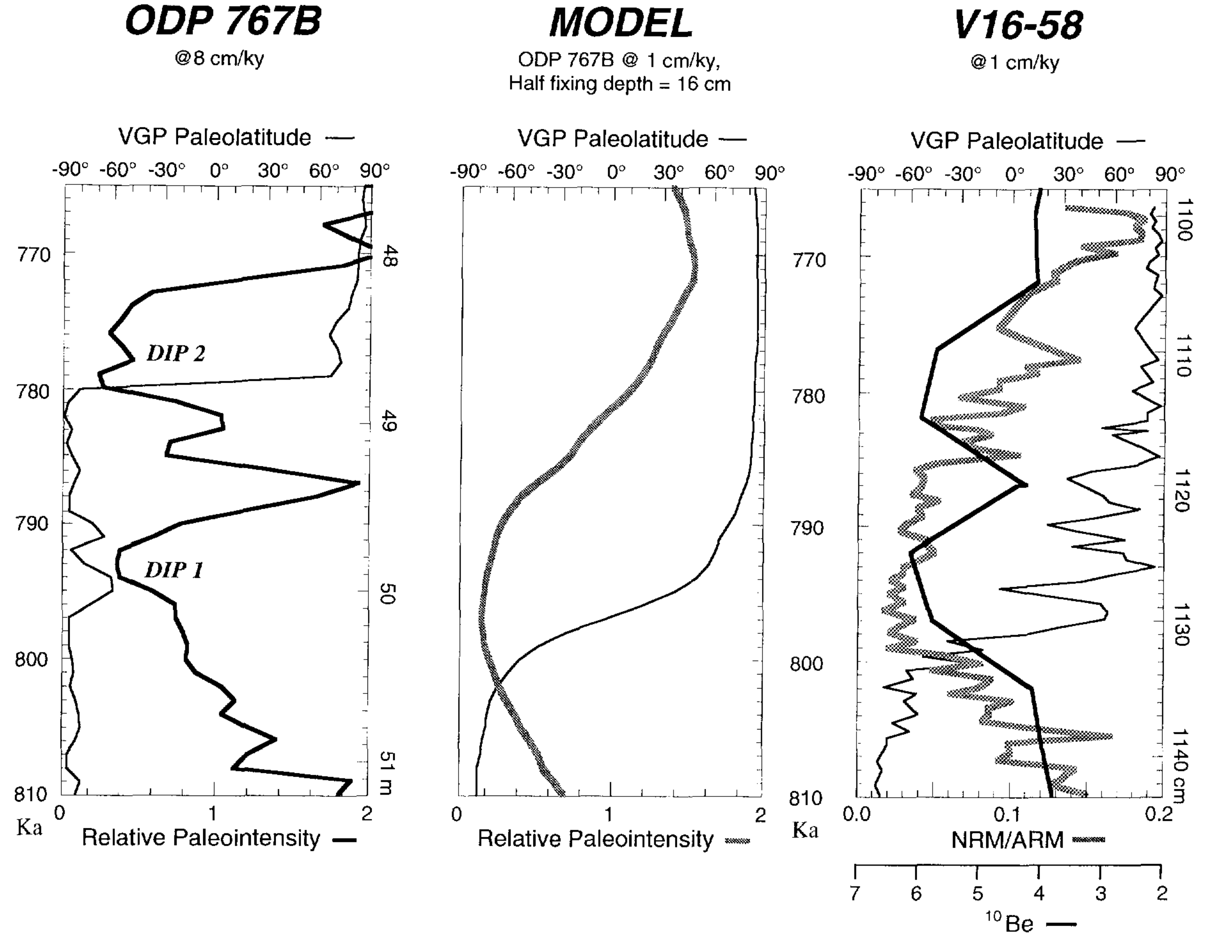


Fig. 2. High fidelity ODP 767B transition record (left, with profiles of VGP latitude and relative paleointensity spline interpolated to 1 kyr intervals), transformed using an exponential lock-in filter [23] with a half fixing depth of 16 cm at a sedimentation rate of 1 cm/kyr (center) to simulate a low-resolution record comparable to that observed in V16-58 (right). Note that the ^{10}Be profile in V16-58 is not subject to the lock-in filter process and, at a sedimentation rate of 1 cm/kyr, the two peaks in abundance of this paleointensity proxy can be correlated with the double DIPs in the ODP 767B record. The ODP 767B (instead of ODP 769A) record was used because it had a longer record length, needed for modeling.

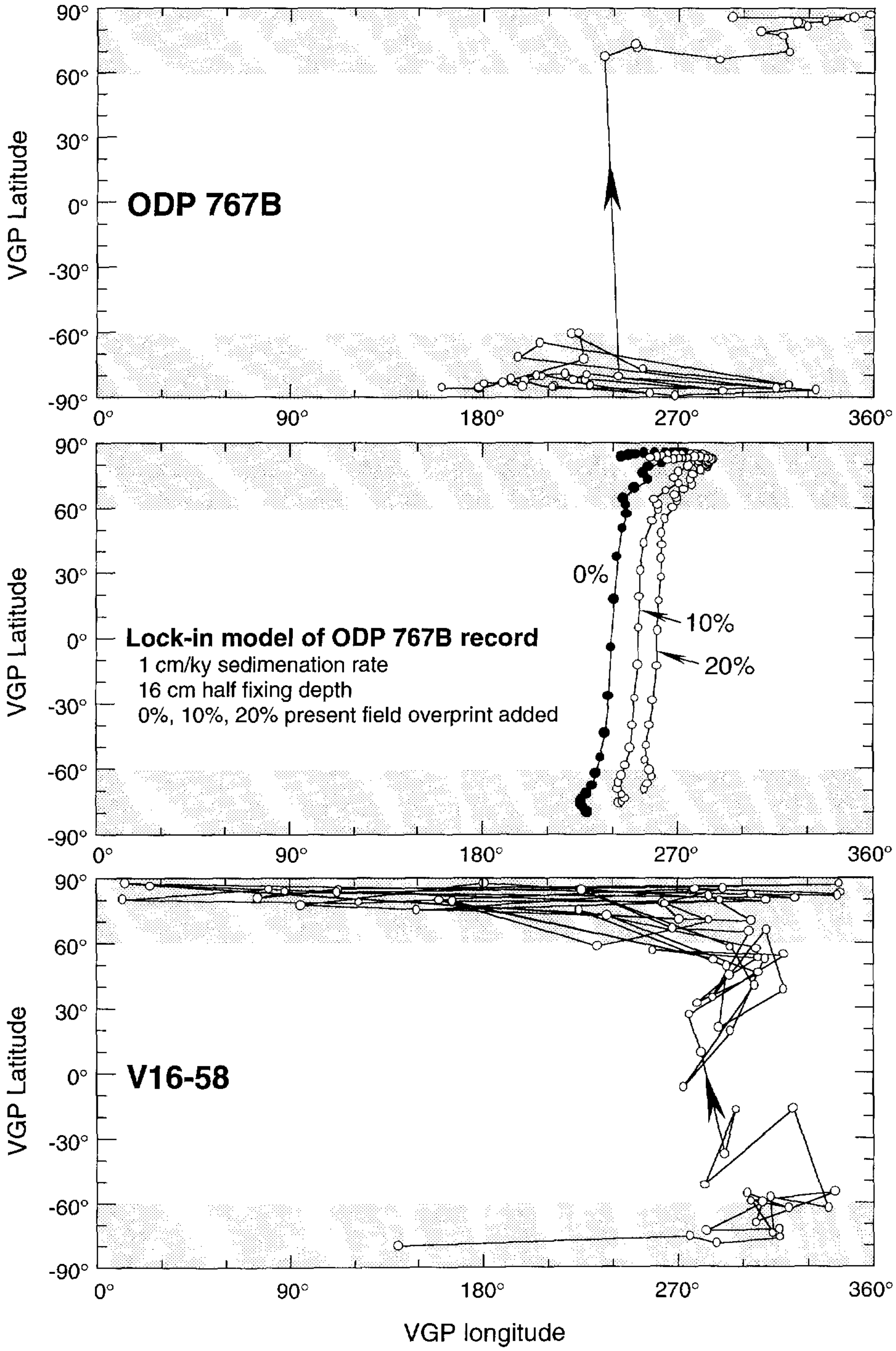
^{10}Be production variations, Raisbeck et al. [14] tentatively attributed the minimum in ^{10}Be concentration at 1120 cm to a significant decrease in the production of ^{10}Be, related to an increase in field intensity within the putative transition interval. Clement and Kent [10] later showed that the ^{10}Be/^{9}Be profile was in reasonable inverse agreement with an ARM-normalized paleointensity record across the B/M boundary in V16-58; there was, however, no increase in paleointensity within the transition to account for the ^{10}Be decrease at 1120 cm, whose significance was, therefore, left unresolved.

The ODP 767B/769A and V16-58 stratigraphic sections can be correlated to each other according to the position of climate Stage 19. The top of this interglacial stage has been placed at 61.9 m in ODP 769A, on the basis of an oxygen isotope record [6,15], and at 1110 cm in V16-58, based only on an indirect climate index [10,16]. At the sedimentation rate of 4 cm/kyr for V16-58 suggested by Clement and Kent [10], the overall increase in ^{10}Be (or ^{10}Be/^{9}Be) would seem to match DIP 2 in ODP 769A (Fig. 1). Absent, however, is any evidence for an expected increase in ^{10}Be production (or ^{10}Be/^{9}Be) between about 1130 and 1190 cm in V16-58 that should correspond to DIP 1 in ODP 767B/769A. Moreover, the low ^{10}Be production at 1120 cm, if real, has no corresponding high paleointensity peak within DIP 2 in ODP 769A.

The ^{10}Be paleointensity proxy record for V16-58 can be reasonably reconciled to the paleointensity record of ODP 767B/769A if we recognize that the sedimentation rates in V16-58 are highly variable and, in fact, poorly constrained. Although rates of ~ 2.5 cm/kyr [14] to 4 cm/kyr [10] have been suggested for the B/M interval on the basis of radiolarian assemblages [16,17], the nominal depth (ca. 1130 cm) to the 0.78 Ma B/M boundary in V16-58 would suggest an overall sedimentation rate of only 1.45 cm/yr. At a sedimentation rate of 1.45 cm/kyr, the interval of generally increased ^{10}Be (or ^{10}Be/^{9}Be) of ~ 30–60 cm would correspond to ~ 20–40 kyr, too long to be linked with the interval of low geomagnetic intensities typically associated with a polarity transition. However, if the minimum in ^{10}Be production at 1120 cm is accepted as valid, the approximately 15 cm separation of the twin peaks in ^{10}Be in V16-58 would be equivalent to about 10 kyr, closer to the 15 kyr wavelengths of the double DIPs seen in ODP 767B/769A; a sedimentation rate of 1 cm/kyr for the B/M interval in V16-58 would optimize the correlation of the twin peaks in ^{10}Be to the double DIPs (Fig. 2). A low sedimentation rate of 1–1.45 cm/kyr would also imply a period of about 34–50 kyr between the carbonate highs documented at about 1090 cm and 1140 cm in V16-58 [17]. Such timing is more compatible with Milankovitch climatic cyclicity over this time interval [18], compared to the timing of 12,500 yr, or about 40% of the shortest (precessional) Milankovitch climate cycle, that would result from the high sedimentation rate of 4 cm/kyr.

A slow sedimentation rate option for V16-58 therefore provides a consistent paleointensity history for these widely separated sites, as would be expected given our conclusion that the ^{10}Be profile in V16-58 and the ODP 767B/769A paleointensity records represent dipole variations. This option does, however, result in a poor match between the paleomagnetic record of the B/M polarity transition in V16-58 and that well documented in ODP 767B and 769A. Transitional directions would seem to characterize most of the early ^{10}Be peak in V16-58, whereas the equivalent interval of low paleointensity (DIP 1) in ODP 767B/769A is represented by fully reversed dipole directions. The B/M polarity transition recorded in V16-58 would, thus, seem to begin earlier and extend over a longer duration compared to the high resolution records of ODP 767B/769A.

We attribute this discrepancy to low-fidelity recording of geomagnetic field behaviour in the V16-58 sediments. Deep-sea sediments generally acquire a magnetization by post-depositional processes [19]. Physical mixing of sediments will displace the magnetization acquisition level toward the base of the bioturbation zone, which radiocarbon studies suggest is about 8 cm in depth [20]. A sediment marker horizon (e.g., microtektite layer or ^{10}Be peak) will also tend to be displaced downward in the bioturbation zone, thus minimizing any depth offset with respect to the bioturbation-displaced magnetic acquisition level to just a fraction of the mixed layer thickness (even though a progressively smaller fraction of the sediment marker will be entrained into subsequently deposited and bioturbated sedi-



ments). Bioturbation alone is, therefore, unlikely to account for the depth depression of 15–20 cm of the V16-58 paleomagnetic record of the reversal (e.g., equator crossing of VGP latitudes at 1130 cm), compared to the ^{10}Be increase centered at ~ 1113 cm, which we believe reflects the actual transition paleointensity low (i.e., corresponding to DIP 2). Similar depth offsets between the B/M reversal boundary and sediment marker horizons have been documented in deep-sea sediments, averaging 16 cm at rates of sedimentation higher than about 1 cm/kyr [7], but apparently ranging to 30 cm and greater in more slowly deposited sediments [21].

Magnetization acquisition will also be governed by the progressive consolidation or increase in effective viscosity of sediments that occurs just below the well-mixed bioturbation zone (e.g., [22]). Although many of the relevant factors are not well understood, this lock-in process is expected to be an exponential function of depth, which can be conveniently parameterized by the half fixing depth [23]. We modeled the geomagnetic field history in ODP 767B at a recording rate of 1 cm/kyr and a half fixing depth of 16 cm (Fig. 2). The double DIPs become a single, broad magnetization low, which, along with the reversal in paleomagnetic directions, occurs about 16 cm (equivalent to about 16 kyr) below the actual level of the polarity transition, similar to what we infer for V16-58. The main features of the ^{10}Be profile will be unaffected by the remanence lock-in process and, consequently, retain its stratigraphic position as a proxy of geomagnetic dipole intensity variation for correlation to the paleointensity record in ODP 767/769A.

If the high sedimentation rate sediments at ODP 767B or 769A had been subjected to a lock-in filtering process characterized by a similar half fixing depth of 16 cm, the time integration of the field and age offset would be comparatively smaller, of the order of only 2 kyr. Short-term intermediate directions may, nevertheless, not be fully represented in the ODP 767B or 769A records, especially if originally acquired in a very weak field (e.g., [24]).

The effects of the remanence acquisition process on transition records have been recognized (e.g., [25,26]) and their importance more recently debated with regard to the significance of longitudinally confined VGP paths [27–29]. The symmetric filters (rectangular or gaussian) used in some of these studies to model the effects of prolonged remanence acquisition in sediments, however, do not produce phase lag to account for the diagnostic depth offset seen in redeposition experiments [30] as well as in the V16-58 record. Indeed, the magnitude of the depth offset provides a good measure of the width of a more appropriate asymmetric lock-in filter.

Less dependent on the exact shape of the filter, however, is the modification of intermediate directions and the production of a magnetization low, due to the progressive combination and self-cancellation of normal and reversed polarity directions. In situations where the characteristic filter width is long relative to the transition, such intermediate directions will be more heavily influenced by the pre- and post-transitional fields than the field configuration during the polarity reversal [26–28]. For example, even though the pre- and post-transition mean directions are within 10° of antipodal and there are few intermediate directions (i.e., VGPs within 60° of the equator) in the high resolution record of the transition interval in ODP 767B (Fig. 3, top), the filtered version modeled to account for the inferred low-resolution recording conditions in

Fig. 3. VGP paths corresponding to the B/M transition record [6] in ODP 767B (top), the spline-interpolated ODP 767B record transformed using an exponential lock-in filter with a half fixing depth of 16 cm at a sedimentation rate of 1 cm/kyr (center), compared to the record [10] from V16-58 (bottom). The center panel also illustrates the effects of adding variable amounts of present-day field overprinting (expressed as a nominal percentage of the mean magnetization intensity of the ODP 767B sediments) to the lock-in model. Note that, while there are few intermediate VGPs (within 60° of the equator) in the ODP 767B record (top), the filter transformation produces many intermediate VGPs along a longitudinal band (center) comparable to the VGP path of the low-resolution record in V16-58 (bottom).

V16-58 is characterized by a series of intermediate directions, giving a longitudinally confined VGP path (Fig. 3, center).

The interval of very low resultant magnetization intensities that can result from the lock-in filtering across a polarity reversal may be preferentially affected by contamination from later overprinting. The VGP path for V16-58 passes through the Americas [10] (Fig. 3, bottom). This corresponds to the longitudinal sector of the modern geomagnetic and magnetic dip north poles (located in the Canadian Arctic) and raises the suspicion of bias by overprinting in the present-day field. The filtered model of ODP 767B gives an apparent VGP path through western North America (ca. 240° longitude), which could signify a slight bias is already present in the pre- and post-transition directions. An overprint in the direction of the local present-day field explicitly added to the resultant magnetization profile will bias the apparent VGP path even closer to the Americas longitudinal sector (ca. 270° longitude; Fig. 3, center). Even when laboratory stability of the magnetizations would seem to exclude viscous remanent magnetization acquisition, an overprint biased in the direction of the present-day field can plausibly result from either much longer term processes (e.g., very gradual physical rotation of the finest magnetic grain-size fraction, or diagenetic alteration and authigenic formation of magnetic minerals [31]) or even very recent and instantaneous events (e.g., partial realignment from earthquake shock or coring) whose effects might be more difficult to recognize and to remove adequately by partial demagnetization techniques. The oscillation of directions within the apparent transition interval of V16-58 may be due to variations in the relative magnitude of a residual overprint.

The often large and significant departures from antipodality documented for pre- and post-transitional directions in many of the Pliocene and Miocene marine sedimentary sections exposed in Crete, Calabria and Sicily may be an indication of more pervasive residual overprints [27]. If overprinting occurred obliquely to the characteristic normal and reversed directions, such as after the sedimentary layers were tectonically tilted or rotated, this could explain nonantipodal declinations which are otherwise difficult to attribute to a regular characteristic of the geomagnetic field in the general absence of evidence for large-scale, non-zonal (e.g., equatorial dipole), polarity-dependent asymmetries in the time-averaged paleomagnetic field [32,33]. Such residual overprints (or other artifacts [29]) would be expected to bias the weaker magnetizations associated with the polarity transitions more seriously, although the resultant VGP paths would not necessarily pass through the Americas.

The ODP 767B/769A records of the B/M polarity transition suggest that the transitional field configuration was dominated by the decay and growth of the reversing axial dipole, similar to the pattern that has recently been generalized for other polarity transition records [34]. The ODP 767B/769A records, moreover, reveal that there is a large paleointensity decrease that preceded the one associated with the B/M polarity transition. This feature can be used to gauge the fidelity of other B/M transition records, provided that they include sufficiently long pre- (and post-) transitional intervals. If the suggested correlation of these decreases in paleointensity with the ^{10}Be paleointensity proxy record in V16-58 is valid, it implies that the paleomagnetic transition record in this slow sedimentation rate core, and the VGP path through the Americas described by these data, are largely an artifact of magnetization lock-in processes. Additional ^{10}Be profiles across polarity transitions, as well as emphasis on independent means of correlation, such as with oxygen isotope stratigraphy, are needed to assess more fully the role of magnetization lock-in processes in modifying the record of the reversing geomagnetic field in deep-sea sediments.

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