Stability of mantle control over dynamo flux since the mid-Cenozoic

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ABSTRACT

Studies of paleomagnetic fields during polarity transitions recorded over the past few million years frequently suggest a configurational persistence consistent with long-lived mantle control over the pattern of flux emanating from Earth’s fluid core. Fundamental to an understanding of the core–mantle dynamics involved is the question of the spatial-temporal nature of the physical conditions at the base of the mantle that may be responsible. Our analysis of the field during a mid-Cenozoic, reverse-to-normal (R–N) polarity change, recorded in a continuous sequence of lava flows in southeastern Queensland, Australia, provides strong evidence that the time span over which local mantle features retain such an influence is far longer than had thus far been observed. Specifically, the reversal is dominated by two sequential groupings of transitional magnetic vector directions, each associated with a clustering of virtual geomagnetic poles (VGSs) at locations common to several more youthful reversal datasets from about the globe. Our 40Ar/39Ar age determinations indicate that these Australian lavas erupted 25.56 ± 0.48 Ma, strongly suggesting that the characteristic time for invariant control by the mantle over flux emerging from the outer core is at least on order of a few tens of Myr. The availability of transitional paleomagnetic data from still earlier times within the Cenozoic may further delineate this duration and, perhaps, provide a means to track changes in the pattern of long-standing concentrations of magnetic flux at the core–mantle boundary.

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1. Introduction

Recordings of the ambient geomagnetic field in rocks during polarity reversals and other geomagnetic events – i.e., at those times when the axial dipole component of the field has significantly weakened – have been found to provide, perhaps, the most easily identifiable paleomagnetic data relevant to the investigation of possible mantle influence over the geodynamo (e.g. Laj et al., 1991; Clement, 1991; Hoffman, 1992; Constable, 1992). For example, clusters of transitional VGPs in and around western Australia are common both to the five records of reversals and events spanning the past 3 Myr obtained from lavas erupted at the Society Islands hot spot (Roperch and Duncan, 1990; Chauvin et al., 1990; Hoffman and Singer, 2004) as well as to several records of the last reversal of the geomagnetic field obtained from sites about the globe (Hoffman, 2000; Brown et al., 2004). Moreover, it has been shown that an inordinately large fraction of Earth’s surface would experience vector field directions corresponding to Australasian south VGPs if the axial dipole of the modern-day field were to vanish (Hoffman and Singer, 2004). The likely explanation for these particular correspondences is that the heterogeneity of the lower-most mantle appears to have held a concentration of magnetic flux, presently at the top of the core off the west coast of Australia (Jackson et al., 2000), in a manner that has remained essentially unchanged since the Pliocene. If so, then analyses of transitional field behavior recorded in rocks from Australasia – i.e., the region on Earth’s surface in closest proximity to this area of the core surface – would be expected to provide the clearest observations of any spatial-temporal changes that may be associated with modifications of the local pattern of mantle-held flux.

Along the Quamby Falls creek bed near Natural Bridge National Park in southeast Queensland, Australia, we sampled some 30 flows over a 200-m thick continuous section (Fig. 1) of a far thicker stack of Tweed Volcano basalts (see Johnson, 1989) (28.2°S, 153.2°E). The age of the complete sequence, determined in the mid-1970s by the K–Ar method, was found to be in the range 22–20 Ma (Wellman, 1975). However, our more precise 40Ar/39Ar age determinations find the eruptive activity to be significantly older than this.
2. \(^{40}\text{Ar}/^{39}\text{Ar}\) age determinations

Groundmass separates of 3 mg each from 10 of the lava flow sites were incrementally heated in 12 steps using a 25 W CO\textsubscript{2} laser at the University of Wisconsin-Madison Rare Gas Geochronology Laboratory. Mass spectrometry and calculation of ages from these experiments follow procedures found in Smith et al. (2006). The age spectra range from concordant (100% of gas defining a plateau) to strongly discordant, with one sample (QF-14) failing to yield a meaningful plateau age. Most other samples yielded spectra with discordant low-temperature steps comprising between 10% and 60% of the gas (Fig. 2). This most likely reflects variable alteration of the basalt matrix. Although many of the isochrons do not give precise \(^{40}\text{Ar}/^{39}\text{Ar}\) intercept values, there is no evidence that excess argon is present in any of these lavas (Table 1).

Notwithstanding the discordant nature of many spectra, the plateau segments from 9 of the samples yield isochron ages ranging from 26.41 ± 0.91 to 23.53 ± 3.02 Ma which, given the 2\(\sigma\) analytical precisions are indistinguishable from one another. Since the lavas record a R–N polarity transition in a continuous exposed sequence, we have pooled the isochron ages of these 9 samples. The weighted mean of the nine isochrons is 25.56 ± 0.48 Ma (MSWD = 1.4), and

![Fig. 1. Sampling site map along Quamby Falls Creek near Natural Bridge, Queensland, Australia.](image1)

![Fig. 2. \(^{40}\text{Ar}/^{39}\text{Ar}\) age spectrum (left) and isochron (right) diagrams for Quamby Falls flow sites 15.0-3B and 9.0-1B. The isochrons are regressed from the plateau data illustrated as dark filled boxes in the age spectra and give the preferred age for these lava flows.](image2)
heated to moderate temperature, and at 650 °C, a very high mean coercivity as illustrated by the first-order reversal curve (FORC) diagrams in Fig. 3(middle). We carried out measurements of continuous thermomagnetic curves (K–T curves) at low- and high-temperature using a cryostat apparatus (CS-L) and a furnace (CS-3) under argon atmosphere coupled to the KLY-3 Kappabridge instrument. Fig. 3(bottom) illustrates and confirms the irreversible thermomagnetic behavior of this primary magnetic phase, characterized by a very low susceptibility. The cooling curve shows evidence for a single magnetite-like phase created during the laboratory heating. We interpret these observations as being due to the presence of a single domain, non-interacting titanohematite phase, which disassociates above 500 °C producing an almost pure fine-grained magnetite (e.g. Shive and Diehl, 1977). This conclusion appears to be supported by microscopic observations of polished sections (Fig. 4). Surprisingly, we did not observe titanomagnetite in some samples, although it is usually the principal opaque mineral contained in lava flows, either because the grains are too small or too few. Instead, we saw numerous, very large laths of ilmenite (>100 m in size), sometimes showing an advanced stage of what appears to be high-temperature oxidation. We tentatively assume that these altered ilmenites host a titanohematite phase compatible with the rock magnetic properties observed in these rocks.

The remanence vector for specimens which showed no sign of containing a titanomagnetite phase typically was found to endure demagnetization to peak alternating fields of >50 mT, occasionally without any noticeable change in either direction or magnitude (see Fig. 5). However, in all such cases there did exist other cored samples from the same flow that do contain titanomagnetite and which demagnetized via alternating field in a more typical fashion for basalts. Most importantly, the resulting vector directions for the two types of observed behaviors were nearly identical, and further demagnetization to high peak alternating fields (<170 mT), followed by thermal demagnetization to steps necessary to completely destroy the remanence, consistently demonstrated unidirectional behavior for all carriers contained in the specimens (Fig. 6). We conclude that regardless of alteration or coercivity characteristics, the recorded paleodirections

### 3. Rock magnetic investigation

At present the carriers of remanent magnetism contained in these lavas are not fully understood. For flows QF9 to QF15 we found the presence – sometimes exclusively – of a magnetic phase having a very high mean coercivity as illustrated by the first-order reversal curve (FORC) diagram in Fig. 3(top). This mineral is unstable when heated to moderate temperature, and at 650 °C appears to be completely transformed into a magnetic phase having a lower mean coercivity (see the FORC diagram in Fig. 3 (middle)). We carried out measurements of continuous thermomagnetic curves (K–T curves) at low- and high-temperature using a cryostat apparatus (CS-L) and a furnace (CS-3) under argon atmosphere coupled to the KLY-3 Kappabridge instrument. Fig. 3 (bottom) illustrates and confirms the irreversible thermomagnetic behavior of this primary magnetic phase, characterized by a very low susceptibility. The cooling curve shows evidence for a single magnetite-like phase created during the laboratory heating. We interpret these observations as being due to the presence of a single domain, non-interacting titanohematite phase, which disassociates above 500 °C producing an almost pure fine-grained magnetite (e.g. Shive and Diehl, 1977). This conclusion appears to be supported by microscopic observations of polished sections (Fig. 4). Surprisingly, we did not observe titanomagnetite in some samples, although it is usually the principal opaque mineral contained in lava flows, either because the grains are too small or too few. Instead, we saw numerous, very large laths of ilmenite (>100 m in size), sometimes showing an advanced stage of what appears to be high-temperature oxidation. We tentatively assume that these altered ilmenites host a titanohematite phase compatible with the rock magnetic properties observed in these rocks.

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![Fig. 3. Magnetization data for a sample from flow QF10 calculated from partial hysteresis experiments known as first-order reversal curves (FORCs) represented by contour plots of two-dimensional distribution functions. Hu is a measure of magnetostatic interactions while Hc provides indirect information about the magnetic domain structure—before (top) and after (middle) heating to 650 °C. (bottom) K–T curves at low- and high-temperature.](image url)
in these basalts are primary in nature, acquired at the time of cooling.

4. Paleomagnetic findings relevant to mantle control

The paleomagnetic results for the Quamby section are shown in Table 2. Logs of the variation in declination (D) and inclination (I) recorded during this reversal are shown in Fig. 7 (top). The associated VGPs, determined relative to the late Oligocene location of the site (40.9°S, 151.6°E) calculated from a fixed Indo-Atlantic hotspot reference frame (see Müller et al., 1993) are shown in Fig. 7 (bottom). The transitional field behavior is dominated by two tight groups of sequential virtual poles. The first, VGP Cluster 1, lies off the west coast of Australia, a locality virtually identical to that observed in Pleistocene records obtained from Society Island hotspot volcanics (see Hoffman and Singer, 2004). Following the equatorial crossing, the second grouping of poles (VGP Cluster 2) is found in Siberia. Since the dynamo is blind to the sign of the field (see e.g. Merrill et al., 1996) it is always equally permissible to analyze transitional field structure by way of the “reversed” antipodal locations of the south VGP. When this is done, the virtual poles associated with the second grouping are found in the South Atlantic. Moreover, the north virtual poles of the first cluster and the south virtual poles of the second cluster reside, respectively, in each of the two Southern Hemisphere cluster patch localities claimed to be preferred during transitional times (Hoffman, 1992).

These findings bolster the contention that mantle-held concentrations of flux at the core-surface control the configuration of the transitional field. Moreover, these data strongly suggest that the lifetime of this influence by the lower-most mantle can exist for at least 25 Myr. The correspondence between the first VGP cluster and those recorded in lavas erupted at the Society Island hotspot (see Fig. 8) and elsewhere during several reversals and transitional events spanning much of the Plio-Pleistocene, further suggests that the influence of a particular radial flux feature – for this case

![Fig. 4](image_url) Upper: reflected light photomicrograph (oil immersion) of a polished section showing an oxidized ilmenite grain (flow QF12). Lower: under crossed-nicols. (For interpretation of the references to color in the artwork, the reader is referred to the web version of the article.)

![Fig. 5](image_url) Thermal (upper) and alternating field (lower) demagnetization behaviors for specimens from a core (flow QF12) containing no observable primary titanomagnetite.

<table>
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<th>Flow</th>
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<th>INC</th>
<th>K</th>
<th>ALPH95</th>
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<td>68.9</td>
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<td>72.8</td>
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beneath Australasia – at times can attain a strength that dominates the field on a regional scale (Hoffman and Singer, 2004), and possibly on a global scale, when the axial dipole is sufficiently weak. Recently published ⁴⁰Ar/³⁹Ar ages determined on transitionally magnetized lavas erupted during the Matuyama-Brunhes reversal, when considered alongside the analysis of the modern-day geomagnetic field, suggest that an early phase of the reversal process, regardless of success, is the destruction of the axial dipole (Singer et al., 2005). Moreover, south virtual poles associated with a significant fraction of the area about the globe for the modern-day NAD-field – i.e., the field following removal of the axial dipole term – are found in and around Australia (Hoffman and Singer, 2004). Hence, the NAD-field appears to be largely influenced by the pattern of radial flux presently found beneath Australasia. Further evidence of the significance of this flux pattern comes from the fact that VGPs determined at Australasian sites, when exposed to the modern-day non-dipole field, remain in the vicinity of Australasia.

As no other contemporaneous paleomagnetic field data are as yet available for the Quamby reversal from elsewhere about the globe, it is not possible to resolve in any robust manner the associated pattern of flux responsible. However, independently analyzed global paleomagnetic data (Gubbins and Kelly, 1993) and recent dynamo modeling by Gubbins et al. (2007), tend to support the claims that core–surface flux concentrations persist over geologic time, that they are strongly tied to the seismic structure presently observed in the lowermost mantle, and that their presence is responsible for long-lived patterns in field morphology. Indeed, the present study suggests that the anomalous lower mantle section beneath Australasia may have existed since the late-Oligocene, if not significantly earlier.

Fig. 6. Demagnetization behavior for three specimens from flows erupted during the polarity transition: orthogonal vector diagrams (at left) and normalized magnetization (at right). In each case the specimens were first demagnetized with alternating fields to 170 mT followed by thermal demagnetization to 450 °C.
The characteristics of the D\textsuperscript{−2}\textendash layer beneath Australasia, the focus of a number of seismic tomographic studies, has been found to be highly complex. Reflected shear wave analyses of D\textsuperscript{−2} structure show considerable variation in apparent thickness below this region with a definite thickening toward the east (Kendall and Shearer, 1994). In addition, the core–mantle boundary (CMB) beneath the Tasman has been found to be particularly complex, possibly containing both fragments of subducted lithospheric slabs as well as a possible plume root (Lay et al., 1998), which may cause downwelling and upwelling, respectively, of the local surface–core fluid. In regard to the latter, a partially molten zone characterized by a significant decrease in seismic wave velocities and increase in density has been found to exist within this region of the CMB (Rost et al., 2005). Since magnetic flux is to some extent frozen into the core fluid and must move with it (see e.g. Backus et al., 1996), any local pattern that is found to persist over geologic time need be the result of control exerted from within the D\textsuperscript{−2}\textendash layer (e.g. Bloxham and Gubbins, 1987). It has been proposed that the tracks of transitional VGP paths may be significantly affected by complex flow patterns in the shallow core caused by regionally anomalous physical properties of the core–mantle boundary (e.g. Lay et al., 1998). Fundamental dynamo theory indicates that the source of the observed VGP patches must be maintained by the balance of induction by fluid flow and magnetic diffusion; the timescale is determined by that for changes in flow patterns. Hence, any change in the structure of the D\textsuperscript{−2}\textendash layer (e.g. thickness and/or state) may need to occur prior to any alteration of the flux pattern discernible by way of transitional VGP behavior.

The paleodirectional reversal data from Quamby Falls, Queensland, displaying strong similarities both to those associated with more youthful transitions as well as to the structure of the modern-day NAD-field, strongly suggests that the duration of a near-stasis of a mantle-held flux patch is at least on order of a few tens of Myr. Only the availability of transitional field data, obtained from the vicinity of Australasia and associated with polarity reversals that occurred prior to 25 Ma, can shed further light on the spatial-temporal manner in which the lower mantle exerts its influence over the geodynamo on a regional scale. To date, there is but one such published record (Wellman et al., 1969; Hoffman, 1986), an early-Oligocene R–N transition obtained from a stack of some 60 lava flows erupted at Liverpool Volcano in nearby New South Wales.
The age of the Liverpool lavas, after corrections are made to the original K–Ar determinations (Wellman et al., 1969) (studied in the late 1960s), is $34.6 \pm 1.4$ Ma (2σ). The VGP path for the Liverpool reversal (Hoffman, 1986), determined for the early-Oligocene site locality of 49.7°S, 150.5°E, contains four significant groupings of VGPs. The first of these, a loosely defined cluster residing near the east coast of New Zealand, lies some 75° in longitude from Cluster #1 in the late-Oligocene Queensland record (Fig. 8). If this early VGP cluster is confirmed to be the initial such grouping of transitional VGPs recorded during this reversal, this deviation could signify a recognizable alteration in the pattern of flux leaving the outer core beneath Australasia at the time of reversal onset relative to subsequent reversals. Moreover, this change would have had to occur sometime within the ~9 Myr between eruption of the Liverpool and Quamby Falls lava sequences. Given the potential significance of these earlier paleomagnetic findings, the Liverpool reversal is currently the focus of a comprehensive re-examination.

Acknowledgments

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