Marine magnetic anomalies as recorders of geomagnetic intensity variations

J. Gee^{a,*}, D.A. Schneider^b, D.V. Kent^c

^a *Scripps Institution of Oceanography, La Jolla, CA 92093-0125, USA*

^b *Scientific American, 415 Madison Avenue, New York, NY 10017, USA*

^c *Lamont-Doherty Earth Observatory, Route 9W, Palisades, NY 10964, USA*

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Abstract

In addition to providing a robust record of past geomagnetic polarity reversals, marine magnetic anomalies often show shorter wavelength variations, which may provide information on geomagnetic intensity variations within intervals of constant polarity. To evaluate this possible geomagnetic signal, we compare sea surface profiles of the Central Anomaly with synthetic profiles based on Brunhes age (0–0.78 Ma) paleointensity records derived from deep sea sediments. The similarity of the synthetic profiles and observed profiles from the ultra-fast spreading southern East Pacific Rise suggests that geomagnetic intensity variations play an important role in the magnetization of the oceanic crust. This interpretation is further supported by systematic variations in the pattern of the Central Anomaly at slower spreading ridges, which are entirely consistent with a progressively smoother record of the sediment-derived paleointensity. If the sedimentary records, as calibrated to available absolute paleointensity data, accurately record variations in dipole intensity over the Brunhes, it follows that much of the Brunhes was characterized by geomagnetic intensities lower than either the mean dipole moment for the past 10 ka or the average for the period from 0.05 to 5.0 Ma. Furthermore, the sediment paleointensity records reflect the significant increase in geomagnetic intensity, from a low of $\sim 2 \times 10^{22} \text{ Am}^2$ near 40 ka to a peak value ($11 \times 10^{22} \text{ Am}^2$) at ~ 3 ka, that has been well documented from absolute paleointensity determinations. We suggest that geomagnetic intensity variations may be the most important cause of the rapid changes in the source layer magnetization near the ridge crest and the resultant Central Anomaly Magnetic High.

Keywords: magnetic intensity; magnetic anomalies; paleomagnetism; marine sediments; Brunhes Epoch

1. Introduction

From the initial recognition by Vine, Mathews and Morley that lineated magnetic anomalies measured at sea reflect reversals of the earth's magnetic

field during formation of the underlying crust [1,2], geophysicists have made excellent use of marine magnetic data. In particular, they quickly exploited marine magnetic anomalies to extend the geomagnetic polarity timescale (GPTS) for the entire age of the ocean basins [3]. This age-calibrated pattern of polarity reversals [4] has been invaluable in reconstructing relative plate motions and the tectonic history of the ocean basins.

* Corresponding author. Fax: +1 619 534 0784. E-mail: jsgge@ucsd.edu

In addition to the readily recognizable pattern of polarity reversals, coherent shorter wavelength anomaly variations have been documented in detailed studies of sea surface anomalies in several regions [5,6]. The interpretation of these short wavelength anomalies, or tiny wiggles, remains the subject of debate. Some portion of this high frequency variation undoubtedly arises from complexities of the crustal accretionary process, such as variations in source layer thickness, geochemistry, or degree of alteration [7–9]. However, the linearity and symmetry with respect to the spreading axis and the consistent pattern of some tiny wiggles at multiple spreading segments strongly suggest a field-related origin for some short wavelength anomalies [10,11].

Although short reversals are clearly responsible for some tiny wiggles observed in anomaly profiles, Cande and Kent [12] have suggested that paleointensity variations provide a more general explanation for the ubiquitous occurrence of tiny wiggles in marine magnetic profiles. Because the nature of past geomagnetic intensity variation was only crudely documented at the time of their analysis, Cande and Kent [12] did not directly compare magnetic profiles with a known record of intensity changes. Instead, they argued their thesis by reconciling the general characteristics of tiny wiggles with statistical properties of the geomagnetic field revealed by paleomagnetic studies.

In this study, we present further evidence that the fine structure of marine magnetic profiles may largely result from geomagnetic intensity changes. We do so by comparing marine magnetic data for the Central Anomaly obtained over the ultra-fast spreading southern East Pacific Rise (EPR) with records of Brunhes age (0–0.78 Ma) paleointensity derived from deep-sea sediments. The correspondence between the observed sea surface profiles and those predicted from the sediment paleointensity records suggests that a geomagnetic signal is preserved in the ocean crust. This inference is further supported by systematic changes in the fine structure of the Central Anomaly at slower spreading rates that are compatible with a progressively lower resolution record of the sediment-derived paleointensity record. We suggest that the approximately fourfold increase in geomagnetic intensity since ~ 40 ka may be responsible for much of the magnetization contrast generating

the short wavelength Central Anomaly Magnetic High (CAMH). The sediment records also imply that geomagnetic intensity during the Brunhes was on average lower than the commonly accepted value for the earth's dipole moment, either as determined for the past few thousand years or averaged over the past 5 million years.

2. Geomagnetic intensity variation during the Brunhes

Although detailed records of absolute geomagnetic intensity variations prior to the Holocene are not available, a number of relative paleointensity records spanning all or part of the Brunhes have recently been obtained from deep-sea sediments. For example, Guyodo and Valet [13] have constructed a stacked record of relative paleointensity for the past 200 ky from 17 sediment records that meet commonly accepted reliability criteria [14]. The consistency of these records from widely separated sites suggests that they preserve a record of dipole intensity variations (Fig. 1a). We focus here on two sedimentary records that span the entire Brunhes (Fig. 1b), a composite record from two equatorial Pacific drill sites [15] and a record from the Sulu Sea [16]. Both these records benefitted from the use of oxygen isotope or density (proxy for carbonate content) data to determine the chronology of intensity variations within the Brunhes.

The sedimentary records provide only relative paleointensity variations; however, an estimate of absolute intensity fluctuations may be obtained by comparison of the youngest portion of the sedimentary record with available absolute paleointensity determinations. Comparison of the stacked record of Guyodo and Valet [13] with a recent compilation of absolute paleointensity determinations [17] illustrates the consistency of the two types of data, at least for the past 200 ky (Fig. 1a). As the uppermost portion of the sediment cores is invariably missing or disturbed, direct comparison with the best determined (Holocene) portion of the absolute paleointensity record is generally not possible. Valet and Meynadier [15] converted the relative paleointensity record from the equatorial Pacific to an absolute scale by comparison with the synthetic record (0–140

Fig. 1. (a) Comparison of stacked record of sedimentary paleointensity variations (solid line with 1σ error) since 200 ka [13] and absolute paleointensity determinations ($\circ$) for this interval [17]. (b) Brunhes relative paleointensity records from equatorial Pacific [15] and Sulu Sea [16] deep sea sediments. The stacked record of sedimentary paleointensity variations since 200 ka [13] is shown for reference. The records have been scaled in terms of variations in the virtual axial dipole moment (VADM) by comparison with absolute intensity determinations, as explained in the text.

ka) of Meynadier et al. [18], which had, in turn, been calibrated to volcanic data from the same period. We have adopted this absolute calibration, using archeomagnetic data [19] and the results from a series of cores from the Mediterranean [20] to provide data for the periods 0–10 ka and 10–33 ka, respectively, which are not represented in the original equatorial Pacific record. Because of the much higher accumulation rate of the Sulu Sea sediments ($\sim 10 \text{ cm/ky}$ as opposed to 2 cm/ky for the equatorial Pacific record), the uppermost span of disturbed or missing core represents only the last 4 ka. Calibration of this high resolution record in terms of absolute paleoin-

tensity is straightforward, as the relative variations between 4 and 10 ka in the Sulu Sea record are strikingly similar to the Holocene record of McElhinny and Senanayake [19]. The Sulu Sea record was calibrated directly with the archeomagnetic data, with the absolute paleointensity data for the past 4 ka being used to complete the youngest portion of the Sulu Sea record.

The records from the equatorial Pacific and Sulu Sea agree reasonably well throughout the Brunhes, with high values at the earliest, middle (near 400 ka), and most recent portions of the Brunhes separated by two broad intervening lows (Fig. 1b). Both records reflect the significant increase in geomagnetic intensity, from a low of $\sim 2 \times 10^{22} \text{ Am}^2$ near 40 ka to a peak value ($11 \times 10^{22} \text{ Am}^2$) at $\sim 3 \text{ ka}$, which has been well documented from absolute paleointensity determinations (see recent compilation by Tric et al. [17]). The most notable discrepancy between the equatorial Pacific and Sulu Sea records occurs in the interval from 120 to 190 ka, with the former having a much less pronounced intensity recovery following the low near 200 ka. The similarity of the Sulu Sea record and the stacked record of Guyodo and Valet [13] in this interval suggests that the equatorial Pacific record may underestimate the dipole moment for the period from 120 to 190 ka. Absolute paleointensity determinations are scarce for times earlier than $\sim 40 \text{ ka}$; however, we note that one broad paleointensity low in the sedimentary records is generally consistent with low dipole moments ($3.5 \times 10^{22} \text{ Am}^2$) obtained from volcanic rocks with ages of 460–570 ka from the Eifel region [21]. The overall similarity of the equatorial Pacific and Sulu Sea sedimentary records and their consistency with available absolute paleointensity determinations suggest that these deep sea sediments may provide a first order representation of geomagnetic variations within the Brunhes.

3. Sea surface magnetic anomaly profiles

To examine whether geomagnetic intensity variations can be recognized in sea surface magnetic anomalies, we compare anomaly profiles from the ultra-fast spreading southern East Pacific Rise near

Fig. 2. Comparison of sea surface profiles from the ultra-fast spreading East Pacific Rise near 19.5°S and synthetic models based on paleointensity variations derived from deep-sea sediments. The synthetic profiles incorporate a simple $\text{age}^{1/2}$ depth dependence and a transition width of 1.8 km. NGDC cruise designations are included for reference.

19.5°S with synthetic anomaly profiles based on relative paleointensity variations determined from deep-sea sediments (Fig. 2). Previous studies indicate a simple spreading history for the EPR near 19.5°S throughout the Brunhes [22]. The extremely fast spreading rate (~ 150 mm/yr full rate) also provides the highest possible temporal resolution for evaluating time-dependent changes in crustal magnetization that should be produced by the significant geomagnetic intensity variations inferred from the sedimentary records. The sea surface profiles do

indeed show short wavelength variations within the Central Anomaly that are coherent for more than 15 km along strike. To first order, these variations are also symmetric about the spreading axis, although some features are less distinct on the slower spreading western flank.

For comparison with the sea surface profiles, we calculated synthetic profiles by allowing magnetization to vary laterally in proportion to the relative intensity indicated by the deep-sea sediment records. The paleointensity-derived magnetization series was smoothed by a 1.8 km (full width) running mean to simulate the effects of crustal accretion in a neovolcanic zone with this half width. This value is consistent with the 1.5–2.1 km transition zone width determined from a near-bottom magnetometer survey of the Brunhes/Matuyama boundary at 19.5°S [23] and corresponds to a duration of approximately 25 ky. Despite the potential complexities unrelated to geomagnetic intensity variations of the source layer magnetization, several features of these synthetic profiles based on the sedimentary paleointensity records mimic the sea surface profiles from 19.5°S. For example, the overall pattern appears to reflect the longer scale undulations in paleointensity. In particular, the synthetic profiles based on the equatorial Pacific and Sulu Sea sediment paleointensity records show early, mid- and late-Brunhes highs broken by two long-wavelength lows. This same pattern appears to be captured by most magnetic profiles obtained over the faster spreading eastern side of the rise, especially by the pasc2 data acquired near 19.5°S. Perhaps the most notable feature of the sea surface profiles from the southern EPR is a short-wavelength (8–15 km) magnetic high associated with the ridge axis. Although several explanations have been advanced [9,24], the presence of a similar high in the synthetic profiles suggests that geomagnetic intensity fluctuations may contribute significantly to the magnetization contrast producing this short-wavelength high.

If the sediment records considered here truly reflect variations in the earth's dipole moment, then the same general pattern should be evident in sea surface profiles globally, although slower spreading ridges will preserve only the longer wavelength intensity variations, as a result of the band pass Earth filter [25]. To test the global nature of the sediment-

derived paleointensity signal, we have compiled a series of sea surface anomaly profiles with full spreading rates ranging from approximately 150 to 30 mm/yr (Fig. 3). The profiles selected are all reasonably symmetric about the spreading axis and have a readily recognizable anomaly high over the ridge crest (the CAMH). Each profile was projected normal to the spreading azimuth, resampled at an even spacing, and reduced to the pole using the theta method of Schouten and Cande [26]. For comparison with the sea surface profiles we generated paleointensity-based synthetic profiles at full spreading rates of 150, 120, 90, 60 and 30 mm/yr. The lateral magnetization variations for these synthetic profiles are based on the stacked record of Guyodo and Valet [13] for the youngest portion of the Brunhes; data for the remainder of the Brunhes are based on the average of the equatorial Pacific and Sulu Sea

records. We used a simple age dependent ($\text{age}^{1/2}$) bathymetric variation for the forward models at the faster two spreading rates. Because topographic relief at slow spreading ridges is substantial and does not follow this simple age–depth relationship, we used the observed topography from profile c2802 to generate the paleointensity-based synthetic anomaly for the slowest spreading ridge.

The pattern of early, middle and late Brunhes highs is evident in all but the slowest spreading rate profiles (Fig. 3). Only the CAMH is discernible in profiles from these slow spreading ridges, as might be expected from the substantial width of the transition zone (taken here to be 1.8 km) and the size of individual volcanic features relative to the overall width of the Central Anomaly. This systematic change in the character of the profiles at progressively slower spreading rates closely approximates

Fig. 3. Sea surface anomaly profiles illustrating the character of the Central Anomaly at a variety of spreading rates. All profiles have been reduced to the pole using the theta method of Schouten and Cande [26]. Synthetic profiles based on the sedimentary paleointensity variations (heavy lines) are shown for five representative spreading rates. Note that the synthetic profile for the slowest spreading rate incorporates the observed bathymetric variations from profile c2802. Profiles are identified by the location of the ridge crossing and NGDC designations (where available).

the changes predicted from the paleointensity-based models. More subtle details in the profiles from fast spreading ridges may also correspond to the geomagnetic variations documented in the deep-sea sediment records. For example, a short wavelength low superimposed on the mid-Brunhes anomaly high is apparent on several of the profiles (at spreading rates as low as 85 mm/yr; profile sotw02 in Fig. 3) and may correlate with a similar feature in the sedimentary records.

4. Discussion

Given the potential complexities of the accretionary process and the variability between the presently available sedimentary paleointensity records, the correspondence between observed sea surface anomaly profiles and forward models based on the sediment records appears sufficient to demonstrate that paleointensity changes contribute significantly to the magnetic signature of oceanic crust. As emphasized by Cande and Kent [12], it seems reasonable to expect that some record of the substantial variability in the earth's dipole moment (42% standard deviation over the past 5 million years [27]) would be reflected in the thermoremanent magnetization of the ocean crust. Although it would be difficult to extract detailed information about intensity changes from sea surface magnetic anomalies alone, the marine data provide valuable corroboration of sedimentary paleointensity records, because the anomaly data rely on a different mechanism for recording changes in the earth's magnetic field. Near-bottom magnetic anomaly data, particularly over fast spreading ridges, should yield a higher resolution record of the geomagnetic fluctuations recorded in the ocean crust. Indeed, a recent detailed near-bottom magnetic survey of anomaly 5 in the northeast Pacific has demonstrated the presence of coherent short wavelength anomalies that can be correlated over a distance of ~ 100 km [28]. As more high quality sedimentary paleointensity records and magnetic anomaly data become available, we anticipate that geomagnetic intensity variations may provide additional temporal markers within the Central Anomaly (and in other polarity intervals) that

will facilitate more detailed studies of ridge crest accretionary processes.

The presence of a short wavelength axial magnetic anomaly high in the synthetic profiles based on sediment paleointensity variations suggests that geomagnetic variations may be responsible for much of the magnetization contrast generating the CAMH. The CAMH typically has a wavelength of 8–10 km in sea surface anomaly profiles, but near-bottom magnetic anomaly data require a magnetization reduction within a few kilometers of the ridge axis [24,29]. A number of hypotheses have been advanced to explain the near ubiquitous presence of the CAMH, including geochemical variations [30], bathymetric relief [10], or the presence of short reversed polarity intervals within the Brunhes [31]. A number of studies have regarded low temperature alteration of the source layer as the most likely cause of the magnetization reduction [9,24,29,32]. However, more recent results indicate that even 'zero-age' lavas show signs of significant magnetic alteration [33]. Together with the limited magnetization reduction that can be achieved by low temperature oxidation (50% reduction; [34]), this observation suggests that some other process must also contribute significantly to the magnetization contrast at the ridge axis. We suggest that geomagnetic intensity variations provide the most probable explanation for the rapid changes in the source layer magnetization near the ridge crest.

According to the sediment-based records, geomagnetic intensity through most of the Brunhes Chron was considerably lower than it has been in the last few millennia. That result has, however, been difficult to reconcile with the good correspondence between the mean dipole moment for the past 10 ka (8.75×10^{22} Am²; [19]) and the average for the period between 5.0 and 0.05 Ma (8.67×10^{22} Am²; [27]). Indeed, the near coincidence of the mean dipole moment over these two time scales apparently argues against any systematically lower value for the Brunhes. Yet, in actuality, the archeomagnetic and volcanic absolute intensity data do not provide particularly strong constraints on the geomagnetic intensity for the majority of the Brunhes.

Archeomagnetic materials have yielded a relatively large number of absolute paleointensity determinations with well constrained ages spanning the

last 50 ky [19]. However, the temporal distribution of these data (87% of the data have ages < 5 ka) is such that the average dipole moment calculated for the past 10 ky may be significantly biased by the high geomagnetic intensities prevalent over the past 5 ka. Although based on much sparser data, the archeomagnetic results indicate a significantly lower dipole moment for the interval from 15 to 50 ka (4.44×10^{22} Am²; [19]). The difference between the average dipole moment for these two time periods suggests that data spanning a longer time period may be required to estimate the time averaged dipole moment accurately.

Compilation of absolute paleointensity determinations from volcanic rocks spanning the period from 0.05 to 5.0 Ma provide an estimate of the average dipole moment over longer timescales (8.67×10^{22} Am²; [27]). However, only two paleointensity determinations in this compilation have radiometric ages demonstrably within the Brunhes. Both sites yielded paleointensities approximately equal to or below the time averaged value. Fifteen other estimates included by McFadden and McElhinny [27] appear to be of Brunhes age (i.e., they show normal polarity and have suggestive geologic constraints). Seven of these have paleointensities ranging from 2.96 to 8.84×10^{22} Am², with a mean significantly below the time averaged value. The remaining eight sites, with high paleointensities (11.45 – 25.01×10^{22} Am²), are all from the Hakone volcanics, which have poorly constrained ages [35]. McFadden and McElhinny [27] also consider an additional 24 paleointensity determinations from paleo-slag deposits in Czechoslovakia [36,37], which they presumed to be recording Holocene–Pleistocene geomagnetic intensity. Although the majority of these yielded dipole moments below the time averaged value, we find no compelling reason (nor is any given in the original publications) to assign any particular age to the thermoremanence acquired from combustion of these Tertiary coal deposits.

We suggest that the absolute paleointensity data presently available are consistent with the low average intensity for the Brunhes ($5.22 (\pm 2.0) \times 10^{22}$ Am² and $3.52 (\pm 1.9) \times 10^{22}$ Am² for the equatorial Pacific and Sulu Sea records, respectively) inferred from the calibrated sedimentary records. As discussed above, the coincidence of the dipole moments

averaged over the past 10 ky and over the period from 0.05–5.0 Ma does not preclude lower geomagnetic intensity values for much of the Brunhes. Absolute paleointensity determinations from lava flows on Mount Etna spanning the interval from 60 to 165 ka [17] as well as paleointensity data from the Eifel region in the earlier portion of the Brunhes (460–570 ka; [21]) are compatible with the relative intensity variations derived from deep-sea sediments. However, recent paleointensity determinations from a drill core on Kilauea's east rift zone suggest paleointensities higher than the present day value on Hawaii for most of the interval from 0 to 42 ka (timescale based on a single dated flow, 42 ± 15 ka; [38]). While these results are intriguing, the high paleointensities are apparently in conflict with the global archeomagnetic database, as well as intensity variations inferred from comparison of ¹⁴C and U/Th age determinations [39]. These new results highlight the need for additional absolute paleointensity determinations within the Brunhes in order to evaluate fully the geomagnetic significance of the sedimentary and sea surface anomaly data presented here. Given the paucity of absolute intensity determinations for most of the Brunhes, we suggest that the paleointensity variations defined by high quality sediment records and corroborated by sea surface magnetic anomaly data offer the best available record of geomagnetic intensity variations for this interval. If so, then recent geomagnetic intensity has in fact been considerably larger than the typical Brunhes field. At least for this one aspect of the earth, the present may not prove a key to the past.

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