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Earth and Planetary Science Letters 183 (2000) 375–388

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Marine magnetic anomalies: evidence that 'tiny wiggles' represent short-period geomagnetic polarity intervals

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Received 13 June 2000; received in revised form 2 October 2000; accepted 2 October 2000

Abstract

Since the 1960's, the geomagnetic polarity time scale, which is based on marine magnetic anomalies, has become fundamentally important in geochronology. Despite the importance of marine magnetic anomaly records, there has been longstanding uncertainty about the meaning of the smallest anomalies observed in these records. Small amplitude, short wavelength anomalies are frequently observed in marine magnetic anomaly records across fast-spreading oceanic crust (>50 mm/yr). The origin of these small-scale anomalies (referred to as 'tiny wiggles') has remained controversial over the last 30 years. 'Tiny wiggles' have been interpreted to represent either short-period polarity intervals or large-scale fluctuations in the ancient field intensity. We present palaeomagnetic evidence from a sedimentary record from the North Pacific Ocean, which demonstrates that two short, but clearly resolvable, polarity zones, in addition to a probable geomagnetic excursion, occur within Chron C5n.2n (9.92–10.95 Ma) where three 'tiny wiggles' have been reported on marine magnetic anomaly profiles. Relative palaeointensity data indicate that the field collapsed prior to and during the reversals (and during the excursion) but that it recovered to higher field intensities within the polarity intervals before collapsing to low values at the succeeding polarity transition. This indicates that some 'tiny wiggles' represent real short-period geomagnetic polarity intervals, while others may represent geomagnetic excursions. The existence of such short polarity intervals confirms the predictions of statistical analyses of geomagnetic reversal frequency and indicates that 'tiny wiggles' represent the maximum resolution of geomagnetic polarity intervals in marine magnetic anomaly records.

Keywords: magnetic anomalies; secular variations; reversals; paleomagnetism

1. Introduction

Recognition that sea-floor magnetic anomalies represent periods of alternating geomagnetic field polarity [1] was one of the key observations that led to development of the theory of plate tectonics. The reliability and completeness of the marine magnetic anomaly record is fundamentally important for use of the geomagnetic polarity time scale (GPTS) in geochronology and for understanding the statistical properties of the geomagnetic field. The temporal resolution of marine magnetic anomaly profiles is limited by several factors, including: the width of the neotectonic zone at mid-ocean ridges, spreading rate, cooling rate, the

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PII: S0012-821X(00)00290-9

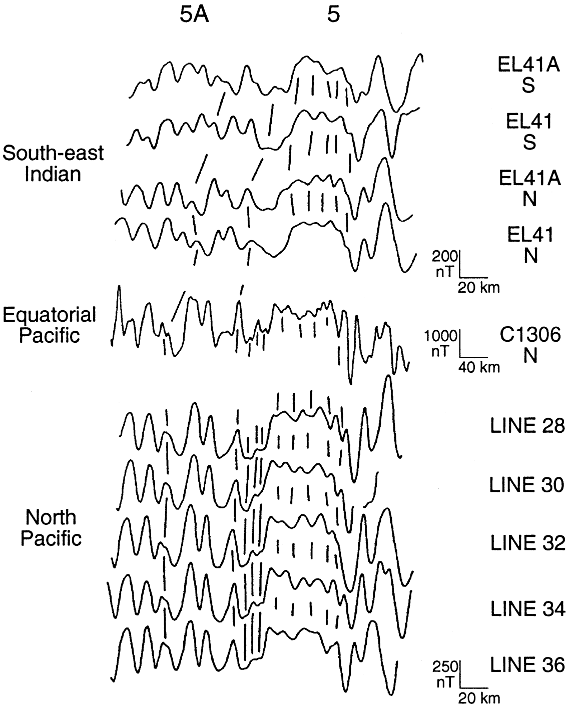

Fig. 1. Marine magnetic anomaly profiles for anomalies 5 and 5A from the South-east Indian, Equatorial Pacific and North Pacific oceans. Correlation of small amplitude, short wavelength features shows the positions of the most prominent ‘tiny wiggles’. Scales and anomaly profile numbers are shown to the right (redrawn from Cande and Labreque [9]). Reprinted by permission from Nature, ©1974 Macmillan Magazines Ltd. (www.nature.com).

depth to the anomaly source and post-eruptive chemical modification of the magnetisation of the anomaly source-rocks. The shortest polarity intervals listed in magnetic polarity time scales are typically of the order of 30 000 years in duration [2–4]. However, statistical analyses of geomagnetic reversal time series predict that shorter polarity intervals must exist in order to give the expected distribution of polarity interval lengths (e.g. 5). Although a continuous distribution of polarity intervals, with a large number of short polarity intervals, is unlikely because inhibition of reversals must occur at some scale [6], the distribution of short-period (<30 kyr duration) polarity intervals remains uncertain. The origin of the shortest period fluctuations observed on marine magnetic anomaly profiles, which are referred to as ‘tiny wiggles’ (Fig. 1), has been debated for over 30 years. Two possibilities have been suggested: ‘tiny wiggles’ represent either short-period polarity intervals [7,8] or large-scale fluctuations in the ancient field intensity [9,10]. The dominant view has been that ‘tiny wiggles’ represent palaeointensity fluctuations [10]. Uncertainty concerning the origin of ‘tiny wiggles’ has resulted in use of the term ‘cryptochron’ to refer to these globally mapped geomagnetic features with durations less than 30 kyr [3,4].

The most obvious means of determining the origin of ‘tiny wiggles’ is to obtain palaeomagnetic records from continuously deposited sedimentary rocks in order to determine the presence or absence of short-period polarity intervals at times where ‘tiny wiggles’ have been reported from marine magnetic anomaly records. In practice, this is not so simple because the temporal distribution of ‘tiny wiggles’ is not uniform. Cande and Kent [4] reported only four ‘tiny wiggles’ in the last 10 Myr (at ca. 0.5, 1.2, 2.43 and 8.64 Ma). There is considerable evidence, from both the northern and southern hemispheres, for the existence of a short polarity interval at 1.2 Ma, which is referred to as the Cobb Mountain polarity interval (e.g. [11–15]). This demonstrates that at least some ‘tiny wiggles’ represent short-period polarity intervals. However, there are few temporally restricted clusters of ‘tiny wiggles’ that can be analysed to rigorously test their origin. The most recent cluster of ‘tiny wiggles’ is a series of three that fall in a single period of normal polarity (Chron C5n.2n) from 9.92 to 10.95 Ma [4] (Fig. 1). ‘Tiny wiggles’ are much more frequent in Eocene–Oligocene magnetic anomaly records. Lowrie and Lanci [16] and Lanci and Lowrie [17] analysed Italian pelagic limestone sequences of Eocene–Oligocene age but observed no short polarity zones coinciding with the positions of expected ‘tiny wiggles’. Hartl et al. [18] and Tauxe and Hartl [19] also analysed nearly continuous sedimentary palaeomagnetic records for an 11 Myr period in the Oligocene, in which a number of ‘tiny wiggles’ have been reported. They concluded that ‘tiny wiggles’ resulted from periods of low palaeointensity that were sometimes accompanied by directional excursions. In all of these examples, however, the sedimentation rates were low (~1 cm/kyr), and it is possible that such short polarity events were smoothed out of the records as a result of sediment remanence acquisition processes (i.e. bioturbation and delays in remanence lock-in). Thus, due to the absence of conclusive palaeomagnetic tests, the origin of 'tiny wiggles' is still uncertain and the preponderance of evidence has been interpreted to favour the hypothesis that 'tiny wiggles' represent global palaeointensity fluctuations.

In this paper, we present results of a detailed palaeomagnetic study of the interval spanning the most recent cluster of tiny wiggles (Chron C5n.2n; Fig. 1) from sediment cores from the North Pacific Ocean. The aim of our study is to determine whether magnetostratigraphic evidence exists for the presence of short polarity intervals within Chron C5n.2n.

2. Geological setting and magnetostratigraphy

The palaeomagnetic records presented in this study are from Hole 884B, which was recovered from the North Pacific Ocean (Fig. 2) during Leg 145 of the Ocean Drilling Program (ODP). Site 884 is located on the flanks of Detroit Seamount on the Meiji Tongue, which is considered to be a drift deposit [20,21] similar to those in the North Atlantic Ocean, where deep thermohaline currents are responsible for the long-term, long-distance transport of sediment. The sediments in Hole 884B are dominated by dark grey clay that yielded consistently high quality palaeomagnetic data (back to ca. 12.4 Ma). Prior to Leg 145, there were no continuously recovered Neogene stratigraphic records from the North Pacific Ocean. Biostratigraphic zonations for this region were therefore based on analyses of tectonically uplifted marine sedimentary sequences, which often contain unconformities, from around the margins of the North Pacific Ocean. Based on the sedimentary records recovered during ODP Leg 145, Barron and Gladenkov [22] developed a detailed North Pacific diatom zonation for the early Miocene to Pleistocene. The magnetostratigraphic records from the Leg 145 sites provide the primary basis for calibration of the diatom biostratigraphy. Agreement in the placement of diatom datums across the North Pacific Ocean [22] provides confirmation of the robustness of the magnetostratigraphic interpretations.

Detailed shipboard palaeomagnetic analyses were conducted by measuring the natural remanent magnetisation (NRM) of the archive halves of the split cores after alternating field (AF) demagnetisation at 15 mT. It is well known that continuous long-core palaeomagnetic measurements can introduce directional artefacts into such records in intervals where remanence intensity undergoes significant variations [23,24]. To avoid this problem, and to confirm the reliability of the magnetostratigraphy, stepwise AF demag-

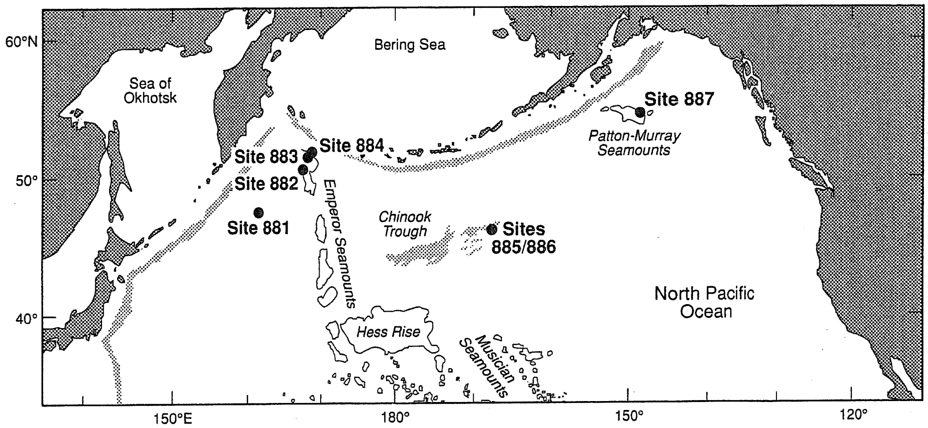

Fig. 2. Location map of the North Pacific Ocean with sites cored during ODP Leg 145, including Site 884.

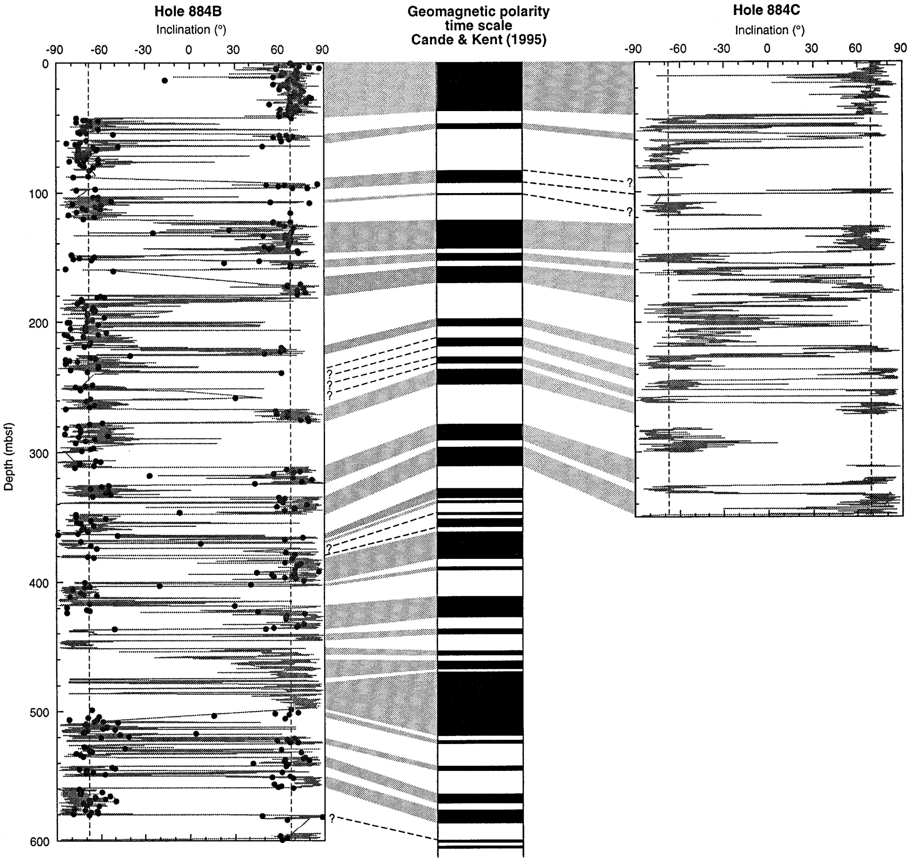

Fig. 3. Magnetostratigraphy of middle Miocene to Holocene sediments from ODP Site 884, North Pacific Ocean. Long-core palaeomagnetic results (after demagnetisation at 15 mT) are shown as a continuous shaded line [15]. Inclinations of the characteristic remanent magnetisation are shown as solid circles for discrete samples. The discrete sample data clearly verify the long-core results. Together, these data delineate the magnetic polarity stratigraphy at Site 884 from 12.4 Ma to present. For the sake of clarity, no discrete sample data are shown for the interval containing C5n.2n (ca. 440–500 mbsf); these data are shown below in Fig. 6. The GPTS represented by black (normal polarity) and white (reversed polarity) stripes is that of Cande and Kent [4]. Dashed lines are used where correlation between the Site 884 magnetostratigraphy and the GPTS is ambiguous. Dashed lines at inclinations of ±68.3° indicate the expected inclination for an axial dipole field at the latitude of Site 884 (51.5°N).

netisation was conducted on 803 discrete samples (6.6 cm^3 volume). These data confirm the reliability of the long-core results (Fig. 3). In addition to the magnetostratigraphic results published by Weeks et al. [15], 342 discrete samples were analysed in this study to confirm the long-core results from the lower part of Hole 884B. Of these, 208 samples were from the interval around Chron C5n.2n which was used to study the origin of 'tiny wiggles'. The cores are azimuthally unoriented and palaeomagnetic polarity is defined on the basis of inclination data, which consistently lie near the expected inclination (±68.3°) for an axial dipole field at the latitude of Hole 884B (51.5°N; Fig. 3).

Apart from occasional intervals of poor core recovery (e.g. at 88–93 m below sea floor (mbsf) (upper Olduvai subchron) and 160–170 mbsf (Mammoth subchron)), the magnetic polarity record is nearly complete and represents a recording of the geomagnetic field from 12.4 Ma to the present (Fig. 3). Sedimentation rates were relatively uniform over long periods of time (Fig. 4) and averaged, respectively, about 5.2 cm/kyr be-

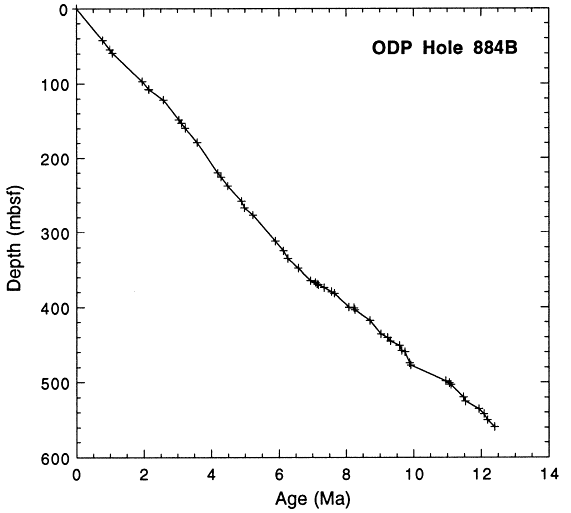

Fig. 4. Sedimentation rate curve for Hole 884B, as indicated by the magnetostratigraphic interpretation given in Fig. 3. Sedimentation rates increased from 3.6 to 5.2 cm/kyr at ca. 7 Ma and were highest during the interval between 4 and 2 Ma.

tween 7 Ma and present and about 3.6 cm/kyr between 12.4 and 7 Ma. Within the Pliocene, between 4 and 2 Ma, sedimentation rates were slightly higher than 5.2 cm/kyr (Fig. 4).

The pronounced variations in sedimentation rate observed in Hole 884B are related to large-scale palaeoceanographic changes. The North Pacific Ocean changed from a carbonate-depositing ocean to a silica-depositing ocean in the early Miocene [25]. In the northwest Pacific Ocean, sedimentation rates increased when biogenic silica fluxes increased in the middle of the middle Miocene in response to the switch in silica deposition from the North Atlantic to the North Pacific and Indian oceans (below the beginning of the record shown in Fig. 4). In the late Miocene (at ca. 7 Ma), silica mass accumulation rates increased greatly across the North Pacific Ocean [26] (Fig. 4). Sedimentation rates at other North Pacific sites decreased when the oceanic regime entered the glacial mode in the late Pliocene [26]. Deposition on the Meiji Tongue at Site 884 was controlled by deep-ocean processes and variability in silica flux since the late Pliocene had less important effects on sedimentation rates (Fig. 4).

In terms of the palaeomagnetic record from Hole 884B, polarity zones with short durations of 20 kyr would be recorded over a stratigraphic interval of about 0.6–1 m at sedimentation rates of 3–5 cm/kyr. Such sediment thicknesses are sufficient to record short polarity intervals and to avoid complete filtering by bioturbation and delayed remanence lock-in under normal pelagic conditions (e.g. [27]). We undertook detailed palaeomagnetic analysis of closely spaced discrete samples from the interval in Hole 884B that corresponds to Chron C5n.2n in order to determine whether there is evidence for short polarity intervals that correspond with the three 'tiny wiggles' reported by Cande and Kent [3,4] within this period.

3. Materials and methods

Details of the methods used to determine the original magnetostratigraphy for Hole 884B were described by Weeks et al. [15]. The present study was conducted in the palaeomagnetic laboratory at the University of Southampton. Paleomagnetic measurements were conducted with a 2-G Enterprises cryogenic magnetometer. Stepwise AF demagnetisation was performed, using a Molspin tumbling AF demagnetiser, at peak fields of 5, 10, 15, 20, 25, 30, 40, 50 and 60 mT. Low-field magnetic susceptibility was measured with a Bartington Instruments MS2 Magnetic Susceptibility meter. Anhysteretic remanent magnetisations (ARMs) were imparted to some of the samples using a solenoid that was inserted into the demagnetising coil of the Molspin demagnetiser. A dc bias field of 50 μT and an AF of 100 mT were used to impart the ARMs, which were measured and then AF-demagnetised at 25 and 30 mT. The magnetic mineralogy was investigated by measuring the magnetisation of bulk sediment samples (in fields of 72 mT) during heating in air from room temperature to 700°C (heating at 30°C/min) and then during cooling back to room temperature using a variable field translation balance. Twenty-four samples were subjected to thermomagnetic analysis, of which 20 gave interpretable results.

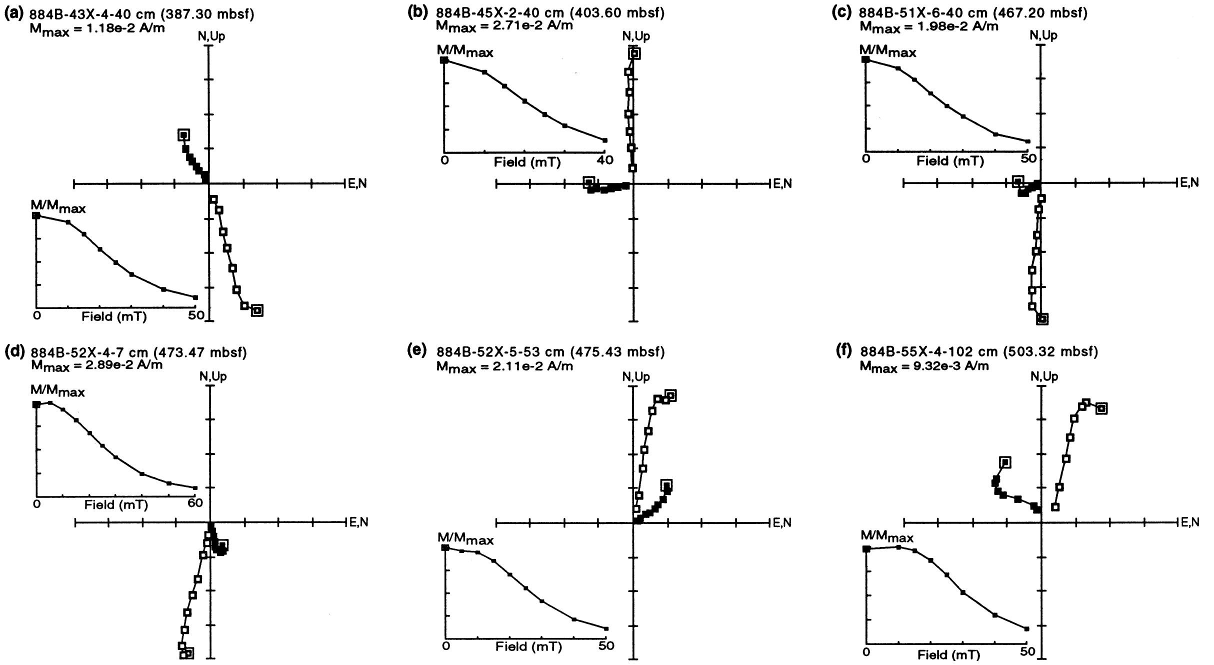

Fig. 5. Vector component plots for typical samples from the interval (387.30 to 503.32 mbsf) in which Chron C5n.2n lies. Open (closed) symbols indicate projections onto the vertical (horizontal) plane. MAD values for these samples vary between 0.9° (c and d) and 2.6° (f).

4. Results

4.1. Paleomagnetic behaviour

For the majority of the samples analysed in this study, the magnetisations are stable and are characterised by univectorial decay to the origin of vector component plots after removal of a small, low-coercivity overprint (Fig. 5). The small magnitude of the overprint provides evidence for why the shipboard palaeomagnetic data, which were obtained after a single-step AF demagnetisation at only 15 mT, yield such a reliable magnetic polarity stratigraphy. For each sample, the maximum angular deviation (MAD; see Kirschvink [28]) of the characteristic remanent magnetisation was calculated after principal component analysis using a minimum of four (and maximum of nine) data points at successive stepwise demagnetisation levels. The MAD for most of the samples is less than 3°. Samples with MADs in excess of 10° have been excluded from the present analysis and those with MADs of 5–10° are explicitly labelled in Fig. 6 to aid discussion of the palaeomagnetic record in the vicinity of Chron C5n.2n.

4.2. Magnetostratigraphy

In almost all cases, the discrete sample measurements closely correspond to the long-core measurements in Hole 884B (Figs. 3 and 6). Solid symbols in Fig. 6 indicate palaeomagnetic directions from discrete samples with MAD values between 5 and 10° and open symbols indicate more stably magnetised samples with $5^\circ < \mathrm{MAD}$. In the lower part of the record shown in Fig. 6, several of the samples with $5^\circ < \mathrm{MAD} < 10^\circ$ lie within polarity transition zones where the magnetisations are relatively weak and where the palaeomagnetic vector is not perfectly defined. In the interval between 453 and 460 mbsf, the magnetisations are weaker and less stable, which contributes to noise in the data and to the discrepancies between the long-core and discrete sample data (Fig. 6). Overall, however, there is general agreement between the discrete sample and long-core data which con-

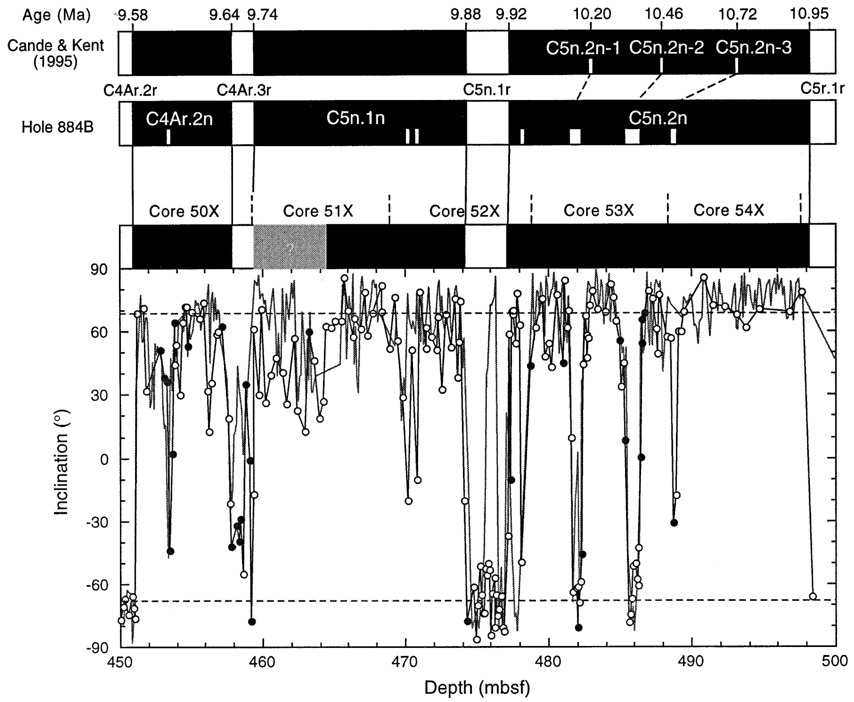

Fig. 6. Detailed magnetostratigraphy for the interval between 450 and 500 mbsf from Hole 884B. Long-core palaeomagnetic results (after demagnetisation at 15 mT) are shown as a continuous shaded line [15]. Inclinations of the characteristic remanent magnetisation directions for discrete samples are shown as circles. Open circles indicate data points with MAD values below 5° and solid circles indicate data points with MAD values between 5 and 10°. The discrete sample data clearly verify the long-core results, although, where there is minor disagreement, the discrete sample data are preferred. The preferred magnetostratigraphic interpretation (see text) compared to the polarity time scale of Cande and Kent [4] and the boundaries between cores (dashed vertical lines) are shown at the top of the figure (black = normal polarity; white = reversed polarity). Reversed polarity cryptochrons (and possible geomagnetic excursions) are shown as short white dashes on the polarity log.

firms the reliability of the long-core measurements.

4.3. Relative palaeointensity of the geomagnetic field during Chron C5n.2n

One of the key issues when testing hypotheses concerning the origin of cryptochrons is to understand how the field intensity varied in addition to whether the field reversed polarity (cf. [18,19]). Roberts et al. [29] described relative palaeointensity results for Pleistocene (0–200 ka) sediments from sites 883 and 884 at Detroit Seamount. Based on extensive measurements of mineral magnetic parameters [30] and general coherence of the resultant relative palaeointensity curves with those from other sites around the world, it was concluded that the Detroit Seamount sediments are suitable for relative palaeointensity studies. The sediments from Chron C5n.2n display similar palaeomagnetic and mineral magnetic behaviour to the late Pleistocene sediments from Site 884. Thermomagnetic analyses from throughout the interval between 472 and 492 mbsf consistently indicate a Curie point near 580°C, which suggests that magnetite is the only significant ferrimagnetic mineral in these sediments (Fig. 7a). In addition, when ARM susceptibility (χ_{ARM}) is plotted versus low-field magnetic susceptibility (χ), the data fall close to a line of uniform slope (Fig. 7b). This indicates that the grain size of the magnetite is sufficiently uniform to enable estimation of relative palaeointensity of the geomagnetic field (cf. [31]). Variation in the concentration of magnetite

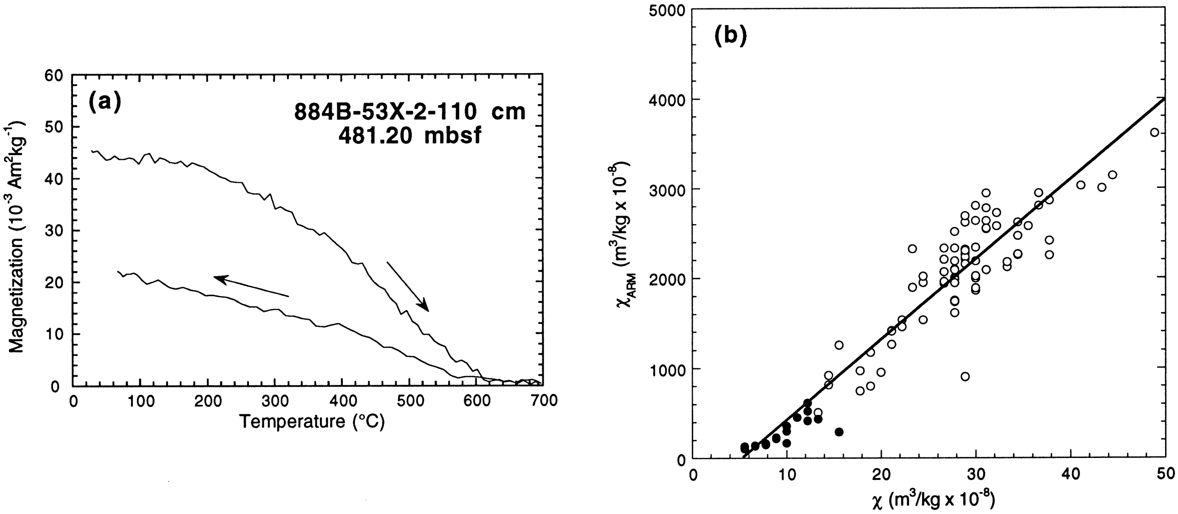

Fig. 7. Plots of (a) magnetisation during heating to 700°C and subsequent cooling to near room temperature, and (b) χ_{ARM} versus χ for samples between 472 and 492 mbsf (for which relative palaeointensity estimates are shown in Fig. 8). The thermomagnetic curve (a) indicates that magnetite is the dominant ferrimagnetic mineral in these sediments and the nearly uniform slope on the plot of χ_{ARM} versus χ (b) indicates that the magnetite grain size is nearly constant. The non-zero intercept of the best-fit line through the data ($R^2 = 0.90$) indicates a paramagnetic contribution to the magnetic susceptibility from matrix minerals (probably clays).

is indicated by the spread of values along the line of constant slope in Fig. 7b; the χ_{ARM} versus χ data fall within two stratigraphically distinct clusters. Low susceptibilities are recorded between 483.5 and 487.5 mbsf (solid symbols), while higher susceptibilities are recorded between 472 and 483.5 mbsf and between 487.5 and 492 mbsf (open symbols; Fig. 7b). χ_{ARM} and χ within these two clusters vary by a maximum of a factor of 7, which is within the limit (factor of 10) suggested by Tauxe [32] for relative palaeointensity studies. The above evidence suggests that it is appropriate to use the NRM/ARM ratio as a proxy for relative geomagnetic palaeointensity in this older interval of the Detroit Seamount record. This conclusion is supported by the fact that identical variations are observed when the NRM (after demagnetisation at 25 or 30 mT) is normalised with more than one parameter (i.e. ARM after demagnetisation at 25 and 30 mT, respectively, and low-field magnetic susceptibility). For the sake of clarity, only one estimate of relative palaeointensity is shown in Fig. 8 (NRM/ARM after demagnetisation of both parameters at 25 mT). The positions of the polarity changes (taken as the point where inclination = 0°) are marked by dashed vertical lines. In each case, the field reversed polarity when the field intensity was close to a minimum.

5. Discussion

5.1. Magnetostratigraphic interpretation between 450 and 500 mbsf

In order to determine whether short polarity intervals are recorded within Chron C5n.2n in Hole 884B, it is necessary to have a clearly defined magnetic polarity stratigraphy. A magnetostratigraphic interpretation for the interval between 450 and 500 mbsf is shown at the top of Fig. 6. For the interval between 453 and 478 mbsf, this interpretation differs from that of Weeks et al. [15], who based their interpretation for this interval on only the long-core palaeomagnetic data. Weeks et al. [15] interpreted the shallow inclination zone at ca. 453 mbsf and the reversed polarity zone between ca. 458 and 460 mbsf to represent chrons C4Ar.3r and C5n.1r, respectively. They also suggested that the top of

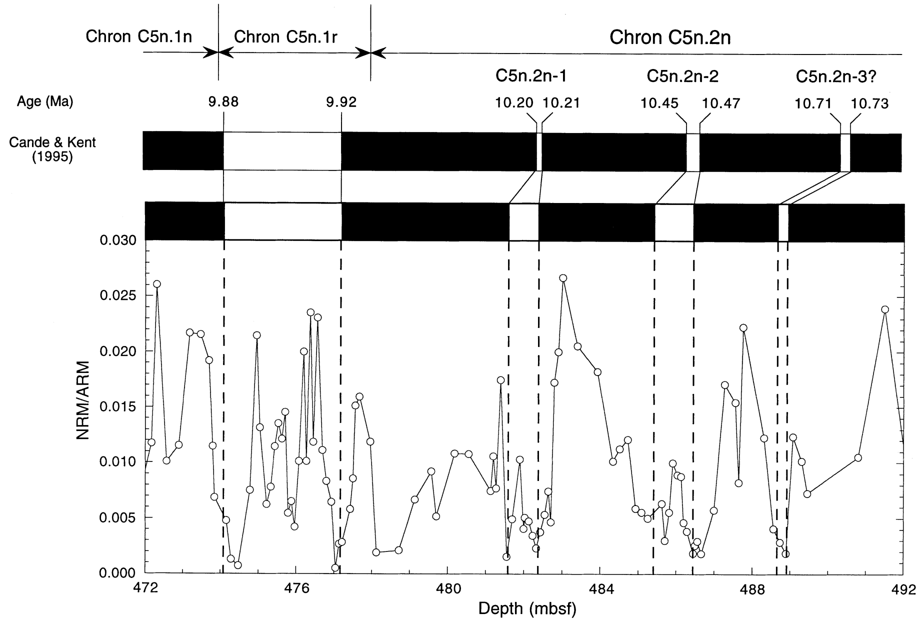

Fig. 8. Estimate of relative palaeointensity of the geomagnetic field (NRM/ARM after demagnetisation at 25 mT) during a portion of chrons C5n.1n to C5n.2n. The three intervals of reversed polarity within C5n.2n are interpreted to represent the cryptochrons C5n.2n-1, -2 and -3. The data indicate that the geomagnetic field collapsed during polarity transitions and that it recovered within two of the cryptochrons before collapsing at the succeeding polarity transition.

Chron C5n.2n lies at 459.50 mbsf and that three short polarity intervals within C5n.2n lie at 474–477, 482 and 486 mbsf, respectively. The interpretation of Weeks et al. [15] is flawed because some magnetozones are unclear (e.g. at ca. 453 mbsf) and yet a polarity interval which should represent less than 30 kyr was recorded over a 3-m interval of the core (474–477 mbsf). Interpretation of the upper part of the record shown in Fig. 6 is partially ambiguous because of an interval with weak magnetisations and relatively high MAD values (solid symbols). We do not interpret the thin zone with shallow reversed polarity inclination at ca. 453 mbsf to represent a true polarity interval because it is only represented by a single sample with an imperfectly defined palaeomagnetic vector. It is indicated as a possible geomagnetic excursion on Fig. 6. Chron C4Ar.3r also lies within an interval of weak magnetisation and is largely defined by samples with MAD values between 5 and 10°. However, this magnetozone is also defined by several samples with MAD $< 5°$ and is therefore likely to represent a true polarity interval (Chron C4Ar.3r). The interval with intermediate polarity samples at ca. 470 mbsf might represent a geomagnetic excursion (Fig. 6), but this remains uncertain because it does not contain more than a single consecutive sample with intermediate polarity. The 3-m-thick interval of reversed polarity from 474 to 477 mbsf is more likely to correlate with Chron C5n.1r than with a cryptochron, as suggested by Weeks et al. [15]. With the interpretation adopted here, Chron C5n.2n lies between ca. 477 and 498 mbsf and contains three intervals in which the geomagnetic field was in either a fully reversed polarity or excursional state, as indicated by two or more samples (Fig. 6).

5.2. Short polarity intervals within Chron C5n.2n?

Despite the above-mentioned ambiguities in the magnetostratigraphic interpretation, the overall agreement between the discrete sample and long-core data is good and confirms the reliability of the long-core measurements. The interpretation shown in Fig. 6 is adopted because it is consistent with the magnetostratigraphic interpretation of the intervals above 450 mbsf and below 500 mbsf (Fig. 3) and because it provides the clearest correlation to the GPTS through the interval between 450 and 500 mbsf (Fig. 6). With this correlation, sedimentation rates must have been slower during Chron C5n.2n compared to the sediments above C5n.2n (compare the dates at the top of Fig. 6). While sedimentation rates appear to have been relatively uniform over longer time periods on the Meiji Tongue (Fig. 4), it is impossible to quantify short-term fluctuations in sedimentation without high-resolution age information. Bianchi and McCave [33] recently showed that sedimentation rates on deep-sea drift deposits can vary by up to a factor of 50 over periods of 10 kyr. It should therefore not be surprising if sedimentation rates also varied considerably over relatively short periods on the Meiji Tongue. Regardless of apparent variations in sedimentation rate, there are more polarity zones between 477 and 500 mbsf than would be expected if cryptochrons do not represent true polarity intervals. The presence of several zones of either excursional or fully reversed polarity directions within Chron C5n.2n provides evidence that the Chron C5n.2n 'tiny wiggles' represent real short polarity intervals (Fig. 6). Two zones of fully reversed polarity and one zone with excursional directions are correlated with the three C5n.2n cryptochrons of Cande and Kent [3,4]. In addition, at the top of C5n.2n (ca. 478 mbsf), there is another excursional interval, which is only indicated by a single sample, which might represent an additional cryptochron. It should be noted that Blakely [8] identified four cryptochrons within C5n.2n, one of which lies at the top of the chron. We refrain from further speculation concerning this excursional interval because it is defined by only a single sample.

Relative geomagnetic palaeointensity determinations provide additional insight into field behaviour during Chron C5n.2n (Fig. 8). The short polarity intervals and excursion shown in Figs. 6 and 8 (C5n.2n-1, C5n.2n-2 and C5n.2n-3) have thicknesses of ca. 0.8, 1.1 and 0.2 m, respectively. Within the upper two of these intervals, it appears that the field collapsed immediately before and during the polarity transition and that it recovered to higher intensities within the polarity zone before collapsing to low values at the succeeding polarity transition. All of these characteristics are consistent with those of true polarity intervals.

The interval that we correlate with cryptochron C5n.2n-3 is represented by a thin (ca. 20-cm-thick) zone with shallow reversed polarity inclinations. The behaviour in this interval is in marked contrast to that of the overlying short polarity intervals. First, the polarity of the field did not fully reverse (Fig. 6) and, second, while the field intensity collapsed to low values, it did not recover before the field returned to a normal polarity state (Fig. 8). These characteristics are more consistent with those expected for a geomagnetic excursion rather than a polarity reversal. It has recently been suggested that geomagnetic excursions result when the field reverses polarity in the Earth's liquid outer core, which has time scales of 500 years or less, but not in the solid inner core, where the field changes on diffusive time scales of 3000 years [34]. In contrast, for a full polarity reversal to take place, the field must reverse polarity in both the inner and outer core. Thus, the palaeomagnetic manifestations of these two phenomena should be, and are, distinct.

The above results suggest that some 'tiny wiggles' represent true polarity intervals that are bounded by two full polarity reversals. This confirms theoretical predictions that there must be shorter polarity intervals than the 30 000 year minimum intervals reported in polarity time scales. The duration of polarity intervals C5n.2n-1 and C5n.2n-2 are clearly long enough that they have not reached a theoretical limit at which inhibition of reversals takes place (cf. [6]) because the field evidently had enough time to reverse polarity and then to recover to higher intensities, as would be expected for a true polarity interval.

5.3. *Durations of the C5n.2n cryptochrons*

The C5n.2n cryptochrons were first identified and dated by Cande and Labreque [9] and Blakely

[8] from fast-spreading marine magnetic anomaly records (Fig. 1). Cande and Kent [3,4] converted the apparent lengths of these 'tiny wiggles' from the North Pacific to a South Atlantic profile, which they used as a template for their time scale. The durations of cryptochrons C5n.2n-1, C5n.2n-2 and C5n.2n-3, as calculated by Cande and Kent [4], are 8, 24 and 16 kyr, respectively. It should be noted that the fast-spreading North Pacific system underwent large, rapid changes in spreading rate and that, with such a variable spreading history, interpolation between age calibration points is problematical. In particular, estimates of cryptochron durations as low as 8 kyr are particularly difficult to use with confidence. If we use the long-term average sedimentation rate of 3.6 cm/kyr for the Hole 884B sediments between 12.4 and 7 Ma, the documented thicknesses of the short polarity intervals in C5n.2n convert to durations of about 23, 28 and 6 kyr, respectively. The durations calculated here for the documented short polarity intervals and excursion that represent C5n.2n-1 to C5n.2n-3 fall within the 30 kyr limit used by Cande and Kent [3,4], which therefore makes them suitable candidates for cryptochrons. It is difficult to match the calculated durations of these cryptochrons as given by Cande and Kent [3,4] to those of the short polarity intervals identified in this study because both data sets are likely to be imprecise for different reasons. The interpolated cryptochron durations given by Cande and Kent [3,4] could be prone to error because spreading rates in fast-spreading crust could have varied considerably during Chron C5n.2n. Additionally, sedimentation rates in Hole 884B seem to have varied on relatively short time scales (Fig. 6), which will produce error in our estimates. It is therefore likely that the discrepancies between the expected durations of the C5n.2n cryptochrons results from a combination of errors in estimating the duration of short-period anomalies from fast-spreading ridges and variable sedimentation rate in this part of Hole 884B.

5.4. Other magnetostratigraphic evidence for short polarity intervals within Chron C5n.2n

Several magnetostratigraphic studies of rapidly deposited continental sedimentary sequences provide independent evidence for the existence of short polarity intervals or excursions within Chron C5n.2n. Garcés et al. [35] documented at least three short reversed polarity intervals within a thick normal polarity interval that they correlated with Chron C5n.2n from the Les Fonts sequence of northeastern Spain. Li et al. [36] studied red bed sediments in the Wangjiashan section in western China and obtained a clear magnetostratigraphy with evidence for three different stratigraphic horizons with reversed polarity within Chron C5n.2n. Rössler and Appel [37] recently obtained magnetostratigraphic evidence for short polarity intervals within Chron C5n.2n from the fluvial Siwalik red beds of Nepal. Roperch et al. [38] also recently identified a short reversed polarity interval in the uppermost part of C5n.2n in fluvial red bed sediments from the Bolivian Altiplano. The age of these sediments is independently constrained by ^{40}Ar/^{39}Ar dating of tuff horizons. Sedimentation rates were extremely high at about 100 cm/kyr and the palaeomagnetic data pass a fold test that attests to the antiquity of the magnetisation. Each of the above cases represent studies of continental sediments in which hematite is interpreted to be responsible for the remanence. The timing of remanence acquisition in red bed sediments is controversial as a result of the possibility of remanence being acquired over long periods of time due to ongoing post-depositional growth of hematite (e.g. [39]). However, several of these studies employed field tests for palaeomagnetic stability, which indicate that the magnetostratigraphic results are reliable. In some of the above cases, the short polarity intervals were not well defined [37], or were identified at only a single stratigraphic level [36] or they occur in intervals where the palaeomagnetic behaviour was not ideal [35], therefore the evidence for short polarity intervals within Chron C5n.2n from these studies must be considered tentative. However, documentation of the same geomagnetic field behaviour from two different depositional environments (i.e. marine sediments (this study) and continental red beds [35–38]) with moderate to high sedimentation rates and with different modes of remanence acquisition provides useful evidence that the Chron C5n.2n 'tiny wiggles' represent real short-period geomagnetic polarity intervals. In addition to the above evidence, McDougall et al. [40] identified an Icelandic lava flow with reversed polarity within the lower part of Chron C5n.2n. While this result was recorded by only a single flow, it provides independent evidence from volcanic rocks that support the conclusion that some 'tiny wiggles' represent real polarity intervals.

5.5. *'Tiny wiggles' and short polarity intervals*

The conclusion that some 'tiny wiggles' represent short-period geomagnetic polarity intervals contrasts with previous magnetostratigraphic studies in which 'tiny wiggles' have been interpreted to represent palaeointensity fluctuations with occasionally accompanying geomagnetic excursions (cf. [18,19]). We attribute this discrepancy to the likelihood that sedimentation rates in the environments used for the previous studies (~1 cm/kyr) were insufficient to provide an adequate test of the hypothesis. Cande and Kent [10] concluded, on the basis of modelling studies, that palaeointensity fluctuations provide a better fit to observed anomaly profiles than a model with short polarity intervals, although they did not exclude the possibility that 'tiny wiggles' represent short polarity intervals.

Cande and Kent [3,4] appropriately designated magnetic anomalies with apparent durations of less than 30 kyr as cryptochrons because of the lack of certainty concerning their origin. Systematic magnetostratigraphic studies of appropriate sediments (with sedimentation rates above ~3 cm/kyr) from a wider range of relevant time intervals are necessary to confirm whether other 'tiny wiggles' represent short-period polarity intervals. The above demonstration that at least some cryptochrons represent short polarity intervals confirms the predictions of statistical analyses of geomagnetic reversal frequency [5] and indicates that the 'tiny wiggles' represent the maximum resolution of polarity intervals on marine magnetic anomaly records. Future analyses of geomagnetic reversal frequency should therefore include the possibility of higher reversal frequency implied by the observation that 'tiny wiggles' represent short-period polarity intervals.

6. Conclusions

Based on palaeomagnetic results from Miocene sediments from the North Pacific Ocean, we make the following conclusions.

1. Two short polarity intervals and a geomagnetic excursion have been documented within Chron C5n.2n.
2. These results provide evidence that some cryptochrons represent real polarity intervals that are bounded by two full polarity reversals rather than periods when the dipole field intensity underwent large-scale variations either with no polarity reversal or only with an accompanying geomagnetic excursion.
3. Future analyses of geomagnetic reversal frequency should include the possibility of higher reversal frequency implied by the observation that 'tiny wiggles' represent short-period polarity intervals.
4. It is necessary to conduct systematic studies of continuously deposited sedimentary sequences with moderate (~3 cm/kyr) or high sedimentation rates to verify whether other 'tiny wiggles' also represent short-period polarity intervals. Such studies will have important implications for magnetostratigraphic analyses in environments with rapid sedimentation rates.

Acknowledgements

We are grateful to the Ocean Drilling Program for allowing access to the cores used for this study and to John Firth for his help in facilitating the sampling. We thank Robin Weeks and Martin Ineson for fruitful discussions about the Leg 145 palaeomagnetic data, Kevin Padley and Antony Pout for technical support, and Richard Blakely, Steve Cande and an anonymous reviewer for critical reviews that helped to improve the paper. We also acknowledge the UK

NERC for enabling sampling at College Station. ***[RV]***

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