Geomagnetic field intensity and reversals during the past four million years

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A long and continuous record of the geomagnetic field intensity shows that intensity variations are dominated by two modes. Major episodes of field regeneration prevail on timescales of a few thousand years immediately after most reversals, whereas stable polarity states are characterized by a slow (~0.5 Myr) relaxation process. Reversals can be seen as the consequence of a progressive degradation of the dipole field.

SINCE the publication of the first detailed geomagnetic polarity timescale for the past 5 million years (Myr) (ref. 1) no major changes have been introduced in the succession of polarity reversals for this period. The existence of very short polarity intervals is still debated: several such intervals are relatively well documented[2–7] and widely accepted, whereas others are regarded as speculative or artefacts of magnetization. Despite these uncertainties, it is fair to say that changes in field direction are relatively well characterized.

A very different situation exists, however, for records of field intensity. With the exception of recent data sets[8–12] obtained for the last few hundred thousand years there is no continuous record showing the evolution of field intensity over a long period of time. This is very frustrating, because this parameter is crucial to constrain the mechanisms associated with the regeneration of the geodynamo. Among several aspects, we can emphasize the importance of documenting the long-term variations in the dipole field during stable polarity states, the field evolution across reversals or other geomagnetic events, and the influence of the Earth's orbital parameters such as precession.

The aim of this study is to retrace field intensity variations during the past several million years. To achieve this goal, we need long and continuous sedimentary sequences with a precise control and good resolution in time. Sequences drilled during Leg 138 of the Ocean Drilling Program offered the first opportunity of obtaining a continuous record of the relative changes in field intensity during the past 4 Myr.

The most striking observation from this record is the existence of asymmetrical saw-tooth patterns associated with the succession of the geomagnetic reversals. The geomagnetic intensity decreases slowly during the intervals of stable polarity, but recovers rapidly immediately after a polarity change. The time constants associated with the decay and recovery phases can vary by up to a factor of 100 and are probably governed by the intensity and/or the structure of the convective regime within the Earth's liquid core. Within the limits of the record, the lengths of the polarity intervals seem to depend on the field strength which followed the preceeding reversal.

Palaeointensity experiments and results

Sites 848, 851 and 852 of Leg 138 in the equatorial Pacific Ocean were selected on the basis of their detailed magnetostratigraphy[13,14] and because they offered continuous sequences[15] from at least four holes drilled at each site. A detailed time-depth correlation was obtained by N. Shackleton[16] for successive intervals of ~25 kyr after tuning the density variations of the sediment (which reflect the changes in carbonate content) to the insolation curve at 65° N. Measurements were conducted on board R/V *Joides* from the archive halves of the cores. The other measurements were done in the IPGP shielded room from U-channels (1 in square section transparent plastic tubes) with the horizontal 2G pass-through cryogenic magnetometer equipped with high resolution coils. Additional measurements were done on >500 single samples. All these studies involve complete stepwise alternating field demagnetization and analyses of rock magnetic parameters in order to detect changes in the grain sizes and the magnetic mineralogy.

Palaeointensity studies from sediments rely on the assumption that magnetic particles are aligned under the effect of the mag-

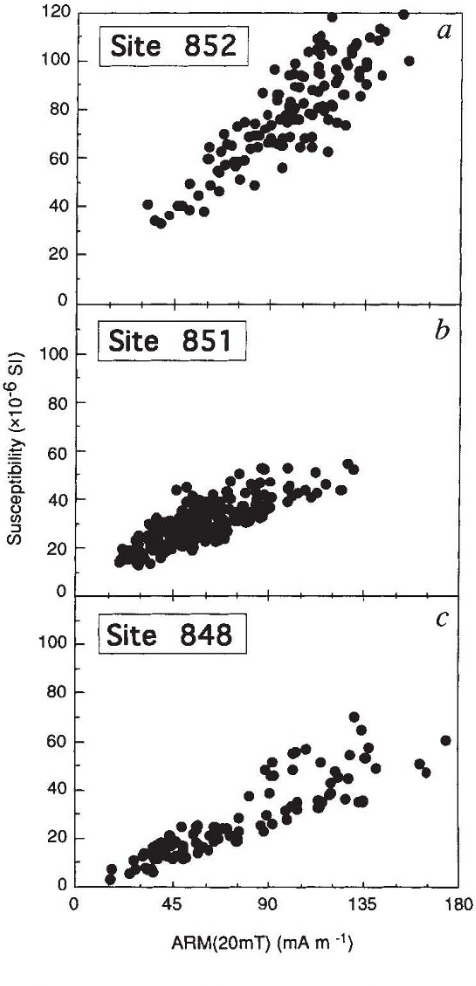

FIG. 1 *a–c*, Plots of anhysteretic remanent magnetism (ARM) against low-field magnetic susceptibility (*K*) for single samples measured at three ODP Leg 138 sites from the equatorial Pacific. The linear relationship between these two parameters indicates a uniform magnetic granulometry at every site. ARM (20 mT) indicates that the ARM was determined after demagnetization at 20 mT.

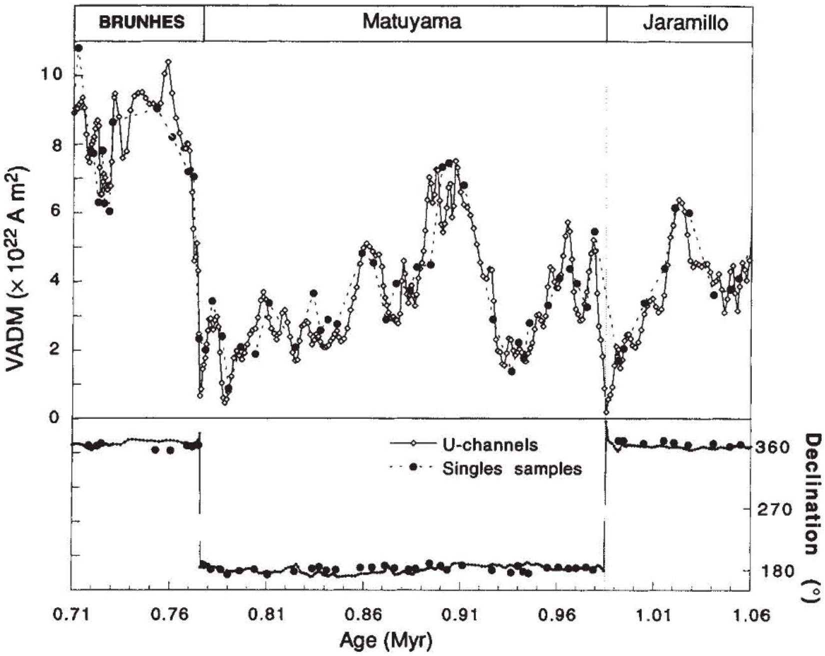

FIG. 2 Declination and relative variations of the dipole field intensity (expressed as VADMs, virtual axial dipole moment, see text) across the Upper Jaramillo and the Matuyama–Brunhes reversals. Note the reproducibility between the measurements of U-channels (measured every 2 cm) and single samples (measured every ~10 cm) obtained from two distinct holes. Very few transitional directions (mostly poorly defined by very weak magnetization intensities) are present.

netic torque exerted by the geomagnetic field so that the magnetic intensity of a sample depends mostly on the field strength and the concentration of magnetic material. Relative field intensities can thus be obtained after normalizing the natural remanent magnetization (NRM) to the amount of magnetic material by using either the anhysteretic remanent magnetization (ARM), the low-field magnetic susceptibility (*K*) or the isothermal remanent magnetization (IRM). Although the ARM (at the same demagnetization level as the NRM) is usually preferred[18,19] we wish to stress that magnetic homogeneity within the column of sediment is a fundamental requirement that implies that identical results should be obtained after normalization by any of these three parameters. Another important requirement for reliability of palaeointensity information from sediments is the acquisition of multiple records. These requirements were satisfied for every site. Identical results were obtained with any of the normalization parameters as shown by the linear relationship of the ARM versus *K* diagrams of the single samples from distinct sites (Fig. 1). There is also a very good reproductibility, not only between distinct holes drilled at every site (Fig. 2), but also between the three distinct sites distributed over 1,000 km. The few intervals with significant changes, montly due to the loss of magnetic signal, were rejected from the final data set. A detailed summary of these experiments and results is given elsewhere[20].

Synthetic palaeointensity record

In Fig. 3, we show our best determination of relative palaeointensity for the past 4 million years (which represents 80 m of sediment) together with the succession of the polarity intervals. As the mean deposition rate does not exceed 2.5 cm kyr^{-1}, we can reasonably assume that the non-dipole components have been averaged out and that the record actually is largely dominated by changes in the intensity of the axial dipole.

Comparisons with other records are extremely limited. Indeed, no other sedimentary record has been published for the period before the Matuyama–Brunhes reversal. The comparison with other records spanning the Brunhes chron[8] or a part of this chron[9] is shown elsewhere[20] and discussed below.

Relative palaeointensities were converted into virtual axial dipole moments (VADMs) after matching the data with the synthetic record of Meynadier *et al.*[11] for the past 140 kyr, which had been calibrated to the volcanic VADMs for that period[10,21,22]. The calibration has been tested also with the volcanic data set recently obtained by Schnepp *et al.*[23,24] for the period 0.45–0.65 Myr before present (BP). Unfortunately, no other detailed volcanic palaeointensities are available for older periods. In the following interpretations, we therefore assume that the downhole response of the sediment to changes in field intensity remained constant. This assumption is supported by the fact that there are no large changes in lithology, mineralogy or deposition rates.

The mean VADM of $3.9 \pm 1.9 \times 10^{22}$ A m^2 is not significantly different from the values calculated for the past 140 kyr ($5 \pm 2 \times 10^{22}$ A m^2) or the period between 15 and 50 kyr BP ($4.3 \pm 1.5 \times 10^{22}$ A m^2) from sedimentary and volcanic data sets respectively[11,12]. It differs, however, by almost a factor of two from the mean VADM deduced from volcanic data for the past 5 Myr (ref. 25). This discrepancy could be partly explained by the relatively low number of absolute palaeointensities (only 150

TABLE 1 Ages of the recent geomagnetic events

Event	Age (Myr BP) Champion *et al.* (ref. 4)	Age (Myr BP) This work	Difference (Myr)
Laschamp	0.042 ± 0.010	0.040	−0.002
Blake	0.114 ± 0.001	0.118	+0.004
Jamaica	0.182 ± 0.031	0.195	+0.013
Biwa II	0.289 ± 0.019	0.280	−0.009
Biwa III	0.389 ± 0.009	0.412	+0.022
Empereur	0.443 ± 0.019	0.419	+0.049
Big Lost	0.565 ± 0.014	0.554	−0.011
Delta	0.635 ± 0.005	0.690	+0.055
Matuyama–Brunhes	0.730	0.780	+0.050
Kamikatsura	0.850 ± 0.030	0.931	+0.081
Jaramillo (upper)	0.910	0.990	+0.080
Jaramillo (lower)	0.980	1.070	+0.090
Cobb Mountain	1.100	1.190	+0.090

Comparison between ages of the excursions, short events, and most recent reversals of the geomagnetic field deduced from the compilation of Champion *et al.*[4] and ages of the intensity lows observed in this work. The offset between the two ranges of dates for ages >0.62 Myr is caused by the recent recalibration of the polarity timescale[20,41]. The differences between the two sets of ages are not larger for excursions and short events than for the reversals.

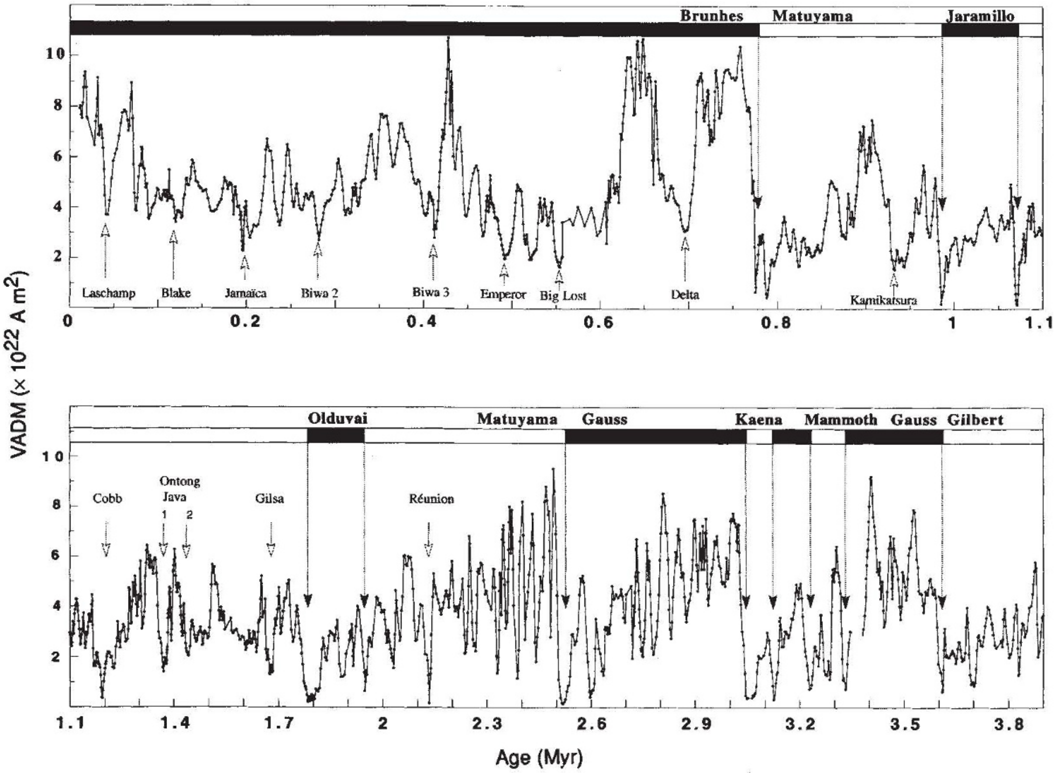

FIG. 3 Relative variations of the dipole field intensity during the past 4 Myr obtained from a composite sequence from ODP Sites 848 and 851. The polarity intervals are indicated by horizontal bars (black/white shows normal/reverse polarities) and the position of the reversals shown by solid arrows. The excursions and the short events observed in previous studies are indicated by open arrows[4,26–28] and correlated with intensity minima of the present record. In order to have a detailed view of the Brunhes chron, the upper and lower figures are not plotted on the same horizontal scale.

determinations) without precise ages in many cases and therefore no control on the regularity of their temporal distribution within this period. The present record indicates also that there is no significant difference between the mean dipole field intensities of the normal and reverse polarities ($4.1 \pm 2.0 \times 10^{22}$ A m^2 and $3.3 \pm 1.5 \times 10^{22}$ A m^2, respectively), given the rather large standard deviations and the fact that the mean normal VADM is slightly biased by the presence of high intensities during the Brunhes chron. We thus prefer to interpret this result as an indication that the two polarity states are equally stable.

The period from 2 Myr BP to the present is characterized by several intensity drops of variable duration which are not correlated with field reversals (Fig. 3). In many cases their occurrences coincide with the ages of geomagnetic field excursions (defined as sudden directional changes followed by a return to the initial polarity) and/or short events (that is, extremely short polarity intervals) shown with open arrows in Fig. 3 which have been reported in several studies for the period 0–1.1 Myr BP and summarized by Champion *et al.*[4] (Table 1). They agree also with recent observations and datings of the Gilsa[26], Cobb Mountain[27] and Ontong Java 1 and 2 events[28] for times before 1.1 Myr BP. Only one large deviation from dipolar directions is observed in the present record of the Cobb Mountain event. The interpretation of transitional directions in terms of short geomagnetic features in weakly magnetized sediments has often been questioned. The observation of field intensity decreases and the fact that intermediate or reverse directions[4,29] have been reported from volcanic sequences for at least some of these events suggest that they could be real geomagnetic features. We notice, however, that other intensity drops are present and not associated with any known event. Additional detailed records would be necessary to clarify further this point.

Saw-tooth intensity changes

The intensity pattern associated with field reversals can be best described as an asymmetric saw-tooth curve (Figs 2 and 3) with a gradual decrease before the transitions and a very rapid recovery immediately following the directional changes. The overall pattern of the record could recall typical numerical solutions of two-disc dynamo systems[30–32]. None of these models, however, predict large quasi-linear intensity decreases but rather an increase (or a decrease) in the amplitude of the oscillations before a reversal. The fluctuations observed in the present record do not show evidence for such amplitude changes but their distribution could suggest the existence of short periodicities. Spectral analyses have therefore been performed on the signals of the rock magnetic parameters (NRM(20 mT), defined as the NRM after demagnetization at 20 mT, ARM, K and ARM(20 mT)/K) and those of relative palaeointensity NRM(20 mT)/ARM(20 mT), NRM(20 mT)/K. The main common characteristic feature is the absence of a stationary

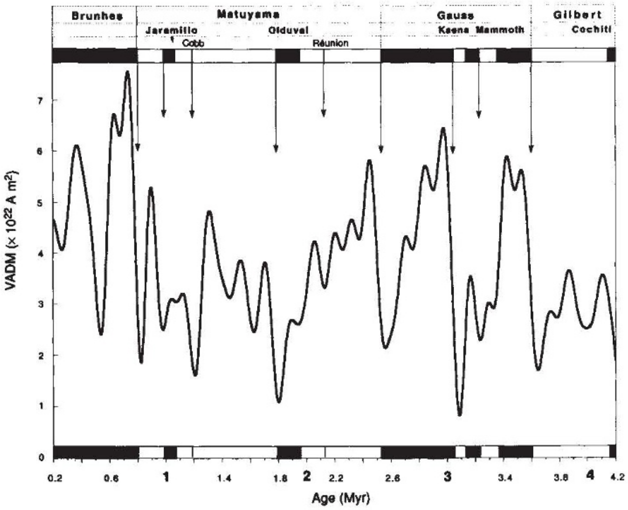

FIG. 4 Record of the dipole field intensity obtained after filtering out the components with periods <125 kyr. The curve depicts the successive episodes of intensity loss and recovery and their relationship to reversals.

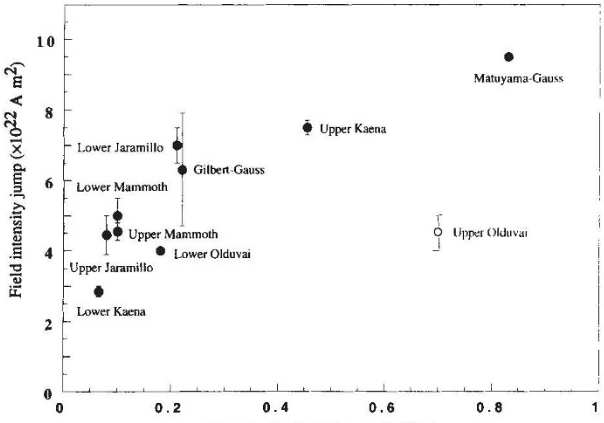

FIG. 5 Relationship between the amplitude of the dipole field following the reversals and the length of the subsequent polarity intervals. The field strength following the upper Olduvai does not fit with the overall tendency (see text).

signal for periods larger than 50 kyr with different frequency spectra for different periods. Although there is no correlation between the rock magnetic parameters and the ratios indicative of relative field intensity, the possible influence of climatically controlled factors should not be underestimated. So far, no appropriate technique is available to detect and extract short-term variations induced by these phenomena. Studies are currently in progress on this aspect.

We can, however, remove most of the energy in the spectra potentially related to climatic modulation by filtering out the higher frequencies (that is, periods <125 kyr of the signal). After this process the 400-kyr Milankovitch component is thus the only climatic periodicity which was not removed. The results shown in Fig. 4 have the advantage of displaying a global aspect of the record and do not show any dominance or superposition of a 400-kyr fluctuation. The first striking feature is that some reversals correspond to particularly large and rapid recovery. Such is the case for the three major reversals that separate the original geomagnetic 'periods': Gilbert–Gauss, Gauss–Matuyama and Matuyama–Brunhes. The intensity recovery occurring at the end of the Kaena subchron appears to be of equal importance. Other reversals are marked by smaller amplitude fluctuations such as the lower and upper Mammoth and Jaramillo. Some other reversals are not associated with a very striking intensity behaviour in Fig. 4: lower Kaena, lower Olduvai or lower Jaramillo; however, those boundaries which are beginnings of short subchrons with typical durations of the order of 100 kyr are in fact accompanied by a smaller intensity recovery which has been smoothed out by the process of filtering and can be clearly observed in Fig. 3. Finally, some short-term events are associated with significant fluctuations which are also more visible in Fig. 3: Cobb Mountain, Ontong Java 1 and 2, Gilsa and Réunion. Three rather regular 'cycles' follow major recoveries at Gilbert–Gauss, upper Kaena and Gauss–Matuyama. The cycle is, however, not so clear for the period following the upper Olduvai with rather a peudo-reverse saw-tooth pattern, but it happens to be more obvious in new, still unpublished, results of another core from the Indian Ocean (MD940). This could be explained by changes in the magnetic homogeneity of the sediment reflected by larger changes in the rock magnetic properties. Indeed, it is striking that the palaeointensity signal was limited to Site 848 for this period and was not duplicated at other sites[20].

Although it does not seem to have been stressed before, the saw-tooth pattern can be taken as a general characteristic of the geomagnetic field. Indeed, if we include the new results of the upper Olduvai, this observation holds for 90% of reversals covered by the present data set. In addition, the same intensity pattern across the Matuyama–Brunhes reversal has now been observed in four distinct marine cores distributed around the world[33]. Similar asymmetry between the decay and recovery phases can be observed in the few detailed palaeointensity records of reversals. Two typical examples are given by the sedimentary records from Crete[34] (6 Myr BP) and the reversal from the Steens Mountain[35] (15 Myr BP) which is the most detailed palaeointensity record obtained so far from a volcanic sequence. A recent study of lava flows from Kauai[36] concludes that the post-transitional lava flows are characterized by stronger palaeofield intensities than the pre-reversal period. Therefore, this observation seems to be an overall and characteristic feature of intensity variations accompanying field reversals.

Despite the presence of a major field recovery after the last reversal, the Brunhes chron seems to be characterized by a more complex behaviour than the rest of the record. Indeed, the very few studies covering this interval published so far[8,9] do not show evidence for a regular decrease of field intensity since the last reversal. Ironically, we noticed that no major polarity reversal has been observed yet since the last one (0.78 Myr BP). It is more appropriate to wonder whether the palaeointensity records are still valid within the first few metres of sediment that are characterized by high water content and thus more subject to physical disturbances and subsequent reorientations of the magnetic grains. Kodama and Sun[37] recently suggested that compaction of sediment can eventually induce an intensity decrease during inclination shallowing. It is possible that the segment of core covering the Brunhes period was not significantly compacted. Although such mechanisms should require a larger amount of clay than in the present cores, the average values of the inclinations (I) of the successive subchrons (for example, $I = 2.2°$ for Brunhes, $I = -4.9°$ from the upper Jaramillo to Matuyama–Brunhes, $I = 3°$ for Jaramillo, $I = -6°$ before Jaramillo) do not show evidence for shallowing in the older parts of the cores.

Characteristic times

The typical time constants of the saw-tooth cycles range between 0.5 Myr and 1 Myr in Fig. 4 (recall that periods <125 kyr have been filtered out) and seem to correspond to some kind of relaxation process. These time constants are significantly longer than the slower modes of free diffusion of the field and could therefore be related to the free decay of the convective core regime itself.

Recovery times are smoothed in Fig. 4 and so must be estimated from the original record of Fig. 3. The best determinations for intervals with high deposition rates indicate a field change between 1 and 2×10^{22} A m^2 kyr^{-1}, that is similar to the decrease of the dipole field over the past 2,000 yr. If effects due to smoothing of the signal induced by post-depositional reorientation of magnetic grains are taken into account, these rates could be as high as 8×10^{22} A m^2 kyr^{-1} (assuming a blocking depth of magnetization between 10 and 15 cm (refs 38, 39)). Such values correspond to time constants of 1,000 years only, that is much shorter than diffusion times and therefore necessarily reflect the dynamics of regeneration in the dynamo process. Therefore, we observe a scale factor of about 100 between the extreme time constants associated with the two main phases inducing the high asymmetry of the saw-tooth features.

The pattern of Fig. 4 supports the major chron boundaries. It seems that some reversals are so 'powerful' that field intensity is regenerated for a long time and that the decaying phase can eventually include short events or excursions which have only second or third order consequences for amplitude fluctuations. This would imply that the core kept some memory of these powerful reversals. Within the limits in resolution of the record, we can establish a rough correlation between the amplitude of intensity recovery following the reversals and the duration of the subsequent polarity chrons or subchrons (Fig. 5); the only significant deviation from this relationship is the upper Olduvai but, as we mentioned it before, does not seem to be observed in other data. Therefore, the stability of the polarity intervals seems to depend on the amplitude of field intensity jump which followed the previous polarity transition. If, for some reason a reversal is not followed by immediate large field recovery, there is no stable antipodal polarity and the field reverses again immediately (observed typically after the first swing or directional change accompanying short events and excursions). Conversely a large field recovery will generate a long stable polarity interval. Similar conclusions have been reached on theoretical grounds by Olson and Hagee[40] who suggest that small changes in the intensity or the structure of the outer core convection can result in an irregular pattern of reversals. The nonlinear kinematic dynamo calculations of these authors predict a correlation between field strength and epoch length.

The selective and tantalizing pattern that emerges from our measurements requires additional work and subsequent confirmation (partly obtained already) from marine and volcanic sequences in other parts of the world. Analyses of the Brunhes period remains critical; it is also important to analyse records spanning periods older than the past 4 Myr. If confirmed, our results are likely to provide major constraints to the competing dynamo theories. □

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Geomagnetic palaeointensities during the Cretaceous normal superchron measured using submarine basaltic glass

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High-quality palaeointensity data have been obtained from Thellier–Thellier experiments on recent and Cretaceous submarine basaltic glasses. Whereas the recent samples faithfully yield today's geomagnetic intensity at the site, the palaeointensities for the beginning and end of the Cretaceous normal superchron are only 45% and 25%, respectively, of today's value. The data thus extend the 'Mesozoic dipole low' into the Cretaceous superchron, and confirm that submarine basaltic glass is an excellent material for palaeointensity studies.

LONG-TERM changes in the frequency of polarity reversals of the geomagnetic field are intriguing, but poorly understood, signals of the deep interior of the Earth. Twenty-five years ago, Cox speculated[1] that these changes might reflect long-term changes in the intensity ratio of dipole and non-dipole fields. He suggested that such intensity variations would probably be caused by changes in core–mantle boundary conditions. Most modern studies agree that variations in the thermal boundary conditions imposed on the core by the mantle could alter the fluid flow in the liquid outer core and ultimately change the reversal frequency[2,3]. The mechanism that ties processes at the core-mantle boundary (CMB) to changes in the geomagnetic field, and the exact consequences of these variations, are not well understood and remain the subject of considerable disagreement and speculation. Indeed, the two predominant models that link CMB processes to reversal frequency come to diametrically opposite conclusions. Larson and Olson[4] propose that the fre-

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