Seven thousand year duration for a geomagnetic excursion constrained by $^{230}\text{Th}_{\text{xs}}$

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[1] The duration of geomagnetic excursions may provide important information about the geodynamo. It has proven difficult, however, to assess the exact duration of both excursions and reversals. We combine high-resolution paleomagnetic records from marine sediments with measurements of the $^{230}\text{Th}_{\text{xs}}$ flux to the seafloor in order to better constrain the duration of the Iceland Basin Excursion (IBE). We find the duration of the IBE to be $\sim 7-8 \text{ kyr}$, implying that it is considerably longer than previous estimates for the Laschamp Excursion ($\sim 2 \text{ kyr}$), and more similar in duration to that of full polarity reversals. There may not be, therefore, a characteristic timescale for transitional field configurations that distinguishes excursions from reversals. Citation: Knudsen, M. F., G. M. Henderson, C. Mac Niocaill, and A. J. West (2007), Seven thousand year duration for a geomagnetic excursion constrained by $^{230}\text{Th}_{\text{xs}}$, Geophys. Res. Lett., 34, L22302, doi:10.1029/2007GL031090.

1. Introduction

[2] Full polarity reversals and geomagnetic excursions provide important constraints on the processes that govern the geodynamo. The difference between reversals and excursions may be related to the time scales that control magnetic field changes in the inner and outer core. Gubbins [1999] proposed that an excursion occurs when the geomagnetic field reverses in the fluid outer core, where changes are dominated by fluid flow with a convective overturn time of $\sim 500 \text{ years}$, but not in the solid inner core, where magnetic field changes are dictated by diffusion with a typical time scale of $\sim 3 \text{ kyr}$ [Hollerbach and Jones, 1993]. A full polarity reversal only follows if the reversal in the outer core persists for the characteristic time it takes the reversed field to propagate through the inner core. This hypothesis has been supported by recent studies indicating that the duration of the Laschamp Excursion (LE) [Laj et al., 2000; Channell, 2006; Wagner et al., 2000] and the Iceland Basin Excursion (IBE) [Laj et al., 2006] was around 2 kyr, which is considerably shorter than the average duration of $7.0 \pm 1.1 \text{ kyr}$ estimated for full polarity reversals [Clement, 2004]. These observations suggest two distinct modes of transitional field behavior: excursions are short ($\sim 2 \text{ kyr}$) and result from a field reversal in the outer core only, whereas reversals, which result from a field reversal in both the outer and inner cores, have considerably longer durations.

[3] Geomagnetic excursions have traditionally been identified as periods when the field direction deviates by a critical value from that of a geocentric axial dipole (GAD). We adopt the widely used definition of an excursion as when the virtual geomagnetic pole (VGP) deviates more than 45$^\circ$ from the geographic pole [Verosub, 1977]. It has proven difficult, however, to determine the duration of geomagnetic excursions. Due to the sporadic nature of volcanic eruptions, it is highly unlikely that lavas recorded the rapidly changing field during an excursion in sufficient detail. Marine sediments that continuously recorded the paleomagnetic field are more suitable archives, but the magnetic signal is often influenced by sedimentary smoothing, especially when the sedimentation rate is low, and many sediments do not record excursions for this reason [Roberts and Winklhofer, 2004]. It is also often difficult to accurately define the interval encompassing an excursion, and the recorded signal is often not reproducible in records from neighboring cores. Another complication arises from the fact that a constant sedimentation rate must be assumed between tie-points in the age model for the record. Reliable age tie-points often result from major climatic shifts and consequently are relatively far apart (e.g., in $\delta^{18} \text{O}$ records), which makes it difficult to reliably reconstruct changes in sedimentation rate. Variable sedimentation rates may therefore partially explain why the estimated duration of the IBE (occurring at $\sim 185-190 \text{ kyr}$) varies from less than 2 kyr [Laj et al., 2006] to as much as 10 kyr [Nowaczyk and Antonow, 1997] in different records.

[4] Here we use high-resolution measurements of excess $^{230}\text{Th}_{\text{xs}}$ ($^{230}\text{Th}_{\text{xs}}$) to better constrain the duration of the IBE, which is perhaps the most pronounced excursion in the Brunhes Chron. The flux to the seafloor of $^{230}\text{Th}_{\text{xs}}$, produced in the water column by decay of $^{234}\text{U}$, can be used to reconstruct variations in sedimentation rate between major stratigraphic tie-points inferred from existing age models [Francois et al., 2004]. We have applied this approach to two high-resolution paleomagnetic records of the IBE from ODP sites 1063 and 983 [Knudsen et al., 2006; Channell et al., 1997].

2. Iceland Basin Geomagnetic Excursion

[5] Average sedimentation rates at ODP sites 1063 and 983 were unusually high (>10 cm/kyr) and the sediments recorded the paleomagnetic field with high fidelity. Paleomagnetic studies of discrete samples from Site 1063, Bermuda Rise, Central Atlantic, indicate good agreement between inclination (Figure 1a) and declination (Figure 1b) anomalies recorded in cores 1063A and 1063B during the IBE [Knudsen et al., 2006]. There is a similar agreement between inclination (Figure 1d) and declination (Figure 1e)
records from cores 983B and 983C from Gardar Drift, south of Iceland [Knudsen et al., 2006]. At both sites 1063 and 983, there is a slight misalignment of the records, which arises from subtle differences in sedimentation models for the two holes at both sites. Nevertheless, general agreement between records from neighboring cores indicates that the geomagnetic field was accurately recorded during the IBE at both sites and that sedimentary smoothing of the signal was negligible.

Using a 45° VGP cut-off angle to define the onset and cessation of excursions, we can identify the intervals encompassing the IBE at sites 1063A and 983B. The VGPs from Hole 1063A deviate more than 45° from the geographic pole in the interval 54.85–53.95 mcd (meters composite depth) (Figure 1c). According to these criteria, the IBE is found at 21.20–20.56 mcd in core 983B (Figure 1f).

3. Stratigraphic Tie-Points From ODP Sites 1063 and 983

An age model is required to constrain the duration of the IBE. The age model for Site 1063 relies on orbital tuning of variations in the carbonate content [Grützner et al., 2002]. The carbonate record is tuned to precession cycles (21-kyr cyclicity) and is supported by comparisons with carbonate records from ODP Site 926 [Bickert et al., 1997] (Figure 2a). The major climatic shifts are conspicuous in the carbonate record from Site 1063, and we have therefore a high degree of confidence in the age model with respect to the timing of the major oxygen isotope stages. This is supported by the fact that the IBE is almost synchronous with the boundary between MIS 7 and 6. The tie-points constraining the age model between the major climatic shifts are more ambiguous because the precession-related cycles are weak. Such intermediate tie-points are not used in this study.

For the period of interest in this study, the published age model for Site 983 [Channell et al., 1997] is based on correlation between the oxygen isotopic record of Site 983 and the SPECMAP record of Martinson et al. [1987]. As is the case for Site 1063, the major isotope stages are well defined and the IBE is almost synchronous with the boundary between MIS 7 and 6 (Figure 2b). Nevertheless, the tie-points used to constrain the age model between the
major climatic shifts are considerably more uncertain for Site 983.

4. Use of the $^{230}$Th Approach

To refine the astronomical age models and to determine the exact duration of the IBE intervals at sites 1063 and 983, we use $^{230}$Th$_{xs}$ to constrain the sedimentation rate in the intervals that span the excursion. This approach requires two well-defined tie-points from the orbital stratigraphy between which $^{230}$Th$_{xs}$ can be used to accurately determine changes in sedimentation rate relative to the average sedimentation rate between the tie-points. The degree of lateral redistribution of sediments (e.g., focusing or winnowing) that has occurred between the two age tie-points is determined by the sediment focusing factor, which essentially is the ratio of sedimentation rate to sediment mass accumulation rate (see auxiliary material for further details). Any sediment focusing or winnowing is assumed to have remained constant throughout the period bounded by the age tie-points. We use two tie-points that are conspicuous and well defined at both sites: the middle of MIS 5.5 at 122.5 kyr ($\pm$2 kyr) and the onset of MIS 7.3 at 220 kyr ($\pm$2 kyr) (Figures 2a and 2b). The average sedimentation rate between these two tie-points is high at both sites: 21.9 cm/kyr at Site 1063 and 10.8 cm/kyr at Site 983.

$^{230}$Th is produced by decay of $^{234}$U in the water column, and, because Th is extremely insoluble in seawater, it is immediately removed to the seafloor [Bacon and Anderson, 1982]. The flux of $^{230}$Th to the seafloor is only dependant on the depth of the overlying water and the concentration of $^{234}$U in seawater, both of which are believed to have been reasonably constant over the last several hundred thousand years [Henderson and Anderson, 2003]. The total activity of $^{230}$Th in the sediment is the sum of the $^{230}$Th supported by U in lithogenic material, the $^{230}$Th ingrown from authigenic U, and the $^{230}$Th scavenged by particles in the water column ($^{230}$Th$_{xs}$). The $^{230}$Th$_{xs}$, which can be used to reconstruct the instantaneous sedimentation

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Figure 2. (a) Age model for ODP Site 1063 [Grützner et al., 2002], which is supported by comparisons with a carbonate record from ODP Site 926 [Bickert et al., 1997], Ceara Rise (western equatorial Atlantic). (b) The age model for ODP Site 983 [Channell et al., 1997] relies on correlation between the oxygen isotopic record of Site 983 and the SPECMAP record of Martinson et al. [1987]. The red bars indicate the stratigraphical tie-points used in this study, i.e., the middle of MIS 5.5 and the onset of MIS 7.3, whereas the gray-shaded areas indicate the intervals encompassing the IBE at the two sites.

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1Auxiliary material data sets are available at ftp://ftp.agu.org/apend/gl/2007gl031090. Other auxiliary material files are in the HTML.
Duration of the IBE Based on $^{230}$Th$_{xs}$

Assuming a constant sedimentation rate between the chosen age tie-points gives a duration for the IBE of 4.1 kyr at Site 1063 and 6.0 kyr at Site 983. Based on the orbital time scales alone, it is not possible to assign realistic time scales alone, it is not possible to assign realistic uncertainty to these durations because of the possibility of significant changes in sedimentation rate between the tie-points. $^{230}$Th allows us to assess any changes in sedimentation rate between the tie-points. $^{230}$Th allows us to assess any changes in sedimentation rate between the tie-points. This, in turn, suggests that the $^{230}$Th$_{xs}$ activities are reliable indicators of sedimentation rates. For Site 983B, the focusing factor is 0.4, which suggests that some winnowing took place (i.e., lateral transport of sediments away from the site). We assume that the degree of winnowing at Site 983 was constant in the interval between the two age tie-points.

The duration of the IBE is calculated to be 6.8 kyr (+0.4/−0.5 kyr) at Site 1063 and 7.9 kyr (+0.9/−1.5 kyr) at Site 983. The uncertainties result from a combination of the uncertainty on the timing of the two age tie-points (±2 kyr) and the $^{230}$Th$_{xs}$ uncertainty, which is, in turn, dominated by the assumed 15% uncertainty in the detrital $^{230}$Th/$^{238}$U ratio.

Discussion

Few published records in which the IBE has been unequivocally identified are of sufficient quality to assess its duration. Two records from the North Atlantic as well as two records from the South China Sea indicate a duration for the IBE of ~2 kyr [Laj et al., 2006]. Other records indicate that the IBE lasted several thousand years, including a study from the Greenland Sea indicating that the IBE lasted 10 kyr [Nowaczyk and Antonow, 1997]. However, the paleomagnetic field behavior and the variations in sedimentation rate are not well constrained for this high-latitude record. A more reliable record from Lake Baikal indicates a duration of 6 kyr [Oda et al., 2002], whereas a recent study from ODP Site 919 in the Irminger Basin indicates that the IBE lasted 8 kyr [Channell, 2006], i.e., an estimate similar to that obtained here from nearby ODP Site 983 (7.9 kyr). This range of estimated durations may partly result from variable definitions (such as a 45° cut-off angle) to define the onset and cessation of the excursion or, alternatively, from undetected changes in sedimentation rate between stratigraphical tie-points. The use of $^{230}$Th$_{xs}$ in this study, which allows assessment of sedimentation rate variability in the intervals encompassing the IBE, suggests that the excursion lasted 7–8 kyr.

The exact duration of an excursion is not necessarily independent of the location of the observation site. Recent studies indicate that the duration of polarity reversals may vary systematically with latitude [Clement, 2004], and
possibly also longitude [Leonhardt and Fabian, 2007]. This kind of variability cannot explain the widely variable durations of the IBE reported in the literature, but it is noteworthy that the IBE at the higher latitude site studied here has a slightly longer duration than at the lower latitude site.

[18] Our evidence suggests that the geomagnetic field during the IBE was in a transitional state for \( \sim 7-8 \) kyr, a time span similar to the estimated duration of polarity reversals [Clement, 2004] and even slightly longer than the average duration of the Matuyama-Brunhes (M-B) transition (5200 years) estimated by Leonhardt and Fabian [2007]. A previous study of the M-B transition from ODP Site 983 gave a duration of 5 kyr [Channell and Kleiven, 2000], based on an astronomically calibrated age model, whereas a \(^{40}\text{Ar}/^{39}\text{Ar}\) study of volcanics have suggested an upper limit for the duration of 12 kyr [Singer and Pringle, 1996]. Our observation may seem to challenge the hypothesis of Gubbins [1999] that the probability of a reversal increases abruptly when the outer-core field remains in a transitional configuration beyond a time period that exceeds the characteristic diffusion time of the inner core (\( \sim 3 \) kyr). However, the duration of a \( N \to R \to N \) excursion cannot be directly compared to that of a full \( R \to N \) polarity reversal because the excursional field needs time to switch back to re-establish its original polarity. It is noticeable, nevertheless, that even half of the duration of the IBE determined in this study (\( \sim 3-4 \) kyr) is longer than several individual estimates of the duration of full polarity reversals. This indicates that the period critical for a reversal to proceed is not necessarily determined by the time the field spends in a transitional state during the event. It has been proposed that the M-B transition only came about following a series of field instabilities that initiated 18 kyr before the polarity switch [Singer et al., 2005]. The duration of the field instability and low field intensity period prior to the event therefore may also play an important role as to whether the outcome is a reversal or an excursion.

[19] The Laschamp Excursion (ca 40 kyr) is perhaps the most thoroughly studied excursion. It has not only been documented in numerous marine records [e.g., Laj et al., 2000; Channell, 2006], but also in \(^{10}\text{Be}\) [Muscheler et al., 2005] and \(^{36}\text{Cl}\) [Wagner et al., 2000] records from Greenland ice cores. The duration of the LE has not been quantified using \(^{230}\text{Th}_{\text{ex}}\), but combined evidence from marine sediments and ice cores indicates a duration of \( \sim 2 \) kyr with little compelling evidence to contradict this estimate. Our study suggests that the duration of the IBE was considerably longer than that of the LE. Consequently, the notion that all excursions are short (\( \sim 2 \) kyr or less) and distinctively different in duration from polarity reversals may be misleading. Our results could indicate that there is no characteristic timescale for transitional field behaviour that define excursions, and rather that excursions and reversals could have a continuum of durations.

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References
Muscheler, R., J. Beer, P. W. Kubik, and H.-A. Synal (2005), Geomagnetic field intensity during the last 60,000 years based on \(^{10}\text{Be}\) and \(^{36}\text{Cl}\) from the Summit ice cores and \(^{14}\text{C}\) Quat. Sci. Rev., 24, 1849–1860.
Singer, B., and M. S. Pringle (1996), Age and duration of the Matuyama-Brunhes geomagnetic polarity reversal from \(^{40}\text{Ar}/^{39}\text{Ar}\) incremental heating analyses of lavas, Earth Planet. Sci. Lett., 139, 47–61.
Singer, B., K. A. Hoffman, R. S. Coo, L. L. Brown, B. R. Jicha, M. S. Pringle, and A. Chauvel (2005), Structural and temporal requirements


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