GEOPHYSICAL RESEARCH LETTERS, VOL. 35, L17307, doi:10.1029/2008GL034719, 2008

Geomagnetic excursions: Knowns and unknowns

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Received 17 May 2008; revised 11 July 2008; accepted 30 July 2008; published 12 September 2008.

[1] Geomagnetic excursions are short-lived episodes when Earth's magnetic field deviates into an intermediate polarity state. Understanding the origin, frequency, amplitude, duration, and field behavior associated with excursions is a forefront research area within solid earth geophysics. Recent advances in excursion research are summarized here, and key further research is suggested to resolve major unanswered questions. Improving the global distribution of excursion records, particularly from the southern hemisphere, obtaining high-resolution sedimentary excursion records with good age control from sites with sedimentation rates >10 cm/kyr, obtaining volcanic excursion records coupled with high-precision geochronology, and estimating excursion duration with high chronological precision will all facilitate hypothesis testing concerning the deep earth dynamics that generate geomagnetic excursions. **Citation:** Roberts, A. P. (2008), Geomagnetic excursions: Knowns and unknowns, *Geophys. Res. Lett.*, *35*, L17307, doi:10.1029/2008GL034719.

1. Introduction

[2] Earth's magnetic field varies on a wide range of timescales from micropulsations (<1 s to minutes) to superchrons (>10 Myr). Geomagnetic excursions occur on timescales of a few thousand years, and therefore represent a small part of the spectrum of field behavior. Nevertheless, excursions are one of the less well-understood aspects of field behavior. An excursion is usually defined as a deviation of the virtual geomagnetic pole (VGP) by more than 40–45° from the geographic pole [*Merrill and McFadden*, 1994] or as a deviation of VGPs away from the normal range of geomagnetic secular variation [*Vandamme*, 1994]. Many questions remain about the frequency of excursions (are they rare or common?), their geographic extent (are they global or regional features?), and the type of field behavior they represent (are they dominantly dipolar or non-dipolar, are they related to geomagnetic secular variation or are they aborted polarity reversals, etc.?). Despite the large literature on excursions, a repeated problem is that anomalous data have been emphasized at the expense of less interesting but more robust data, and, combined with poor chronological constraints, "excursion" records are commonly used to estimate the age of a sedimentary sequence. This has led to a "reinforcement syndrome" [*Thompson and Berglund*, 1976] that complicates geomagnetic excursion research. Such problems have also wreaked widespread chronostratigraphic havoc in Quaternary research. After over four decades of geomagnetic excursion research, much is known, but much remains unknown. I give a perspective below on these "knowns" and "unknowns", and suggest further research to address key remaining questions. Any discussion of "knowns" in relation to excursions rapidly strays into "unknowns". I have tried to retain clarity in such situations.

2. Key Questions in Geomagnetic Excursion Research: Knowns and Unknowns

[3] Following editorial directives for this series of brief review papers, I deliberately bias toward citation of recent work. Readers seeking an in-depth, critical appraisal of the excursion literature are directed to the excellent recent review of *Laj and Channell* [2007].

2.1. Why do Excursions Happen?

[4] Detailed geomagnetic paleointensity records indicate that the field frequently collapses to low intensities (Figure 1), which provides an opportunity for the field to either fully reverse polarity or to undergo a directional excursion. What dictates whether the field undergoes a reversal or an excursion? *Gubbins* [1999] suggested that excursions occur when the field in Earth's liquid outer core reverses polarity (on timescales of 500 yr or less), without accompanying field reversal in the solid inner core (where the field changes by diffusion on 3-kyr timescales). The magnetic inertia of the inner core therefore delays full field reversal, during which time the previous polarity configuration becomes re-established in the outer core. This mechanism has become a standard explanation for excursions. Despite the attractiveness of this model, we do not yet know the precise duration of excursions, and further work is needed. In contrast to this hypothesis, numerical dynamo simulations indicate that the inner core is too small for its electrical conductivity to significantly affect dynamo processes [*Wicht*, 2002; *Busse and Simitev*, 2008]. Excursions can also result from an oscillatory dynamo process [*Busse and Simitev*, 2008]. The origin of excursions therefore remains an open question.

2.2. Are Excursions Rare Events?

[5] High-resolution paleomagnetic (including relative paleointensity) and $\delta^{18}O$ analysis of marine sediments or/and radioisotopic dating of volcanic rocks over the last decade have verified the precise age of some excursions (e.g., Mono Lake, Laschamp). New excursions have been identified (e.g., Iceland Basin, Bjorn, Gardar), and poorly dated excursions have been precisely dated (e.g., Pringle Falls, West Eifel) [*Singer et al.*, 2008a, 2008b]. Unverified excursions have been discredited (e.g., Lake Mungo, Gothenburg, Biwa, Jamaica), and others remain to be fully validated and accepted (e.g., Norwegian-Greenland Sea, Calabrian Ridge 0, 1, 2 & 3). Following *Laj and Channell*

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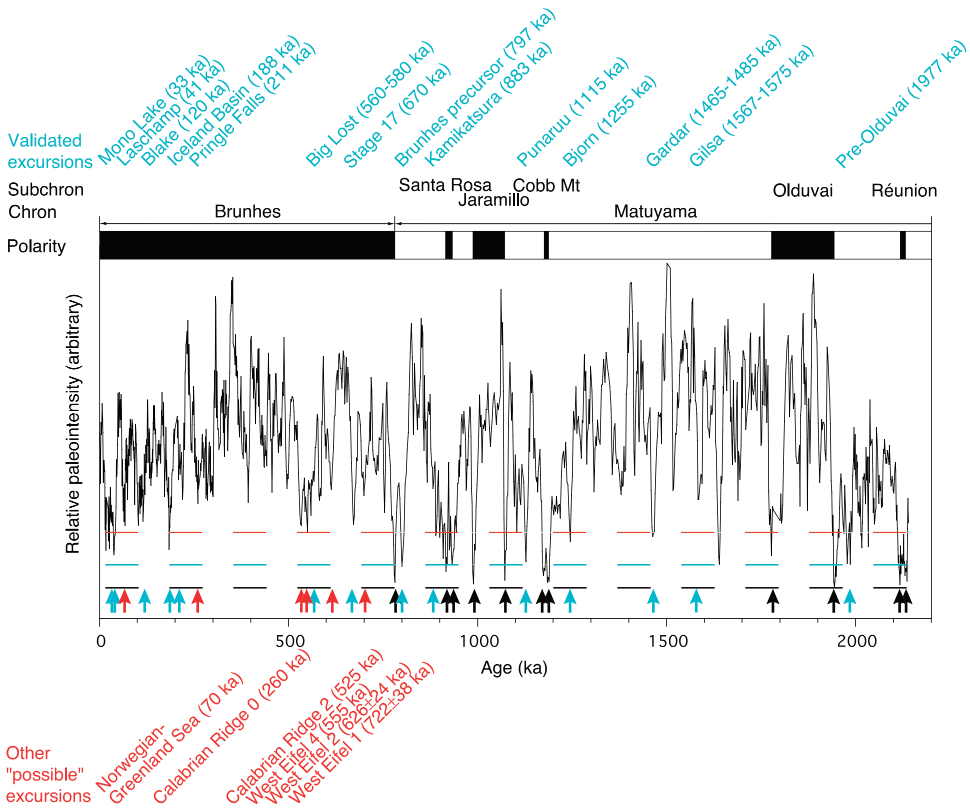

Figure 1. Geomagnetic reversals and relative paleointensity variations (from *Horng et al.* [2003]) for the last 2.14 Ma. Black (white) indicates normal (reversed) polarity. Reversals (black arrows), validated excursions (blue arrows; see *Laj and Channell* [2007] for validation and age control), and "possible" excursions (red arrows) all coincide with paleointensity minima. A Brunhes precursor [*Kent and Schneider*, 1995] is included at 797 ka; the Kamikatsura, Pringle Falls, West Eifel and Big Lost excursion dates are from *Singer et al.* [1999, 2008a, 2008b].

[2007], seven Brunhes Chron excursions are shown as validated in Figure 1, with six others indicated as "possible", rather than the 12 excursions reported by *Lund et al.* [2001]. All validated and possible excursions for the last 2 Ma are associated with paleointensity minima (light blue and red arrows in Figure 1), as are all full polarity reversals (black arrows). Intervals with the lowest paleointensities are associated with full polarity reversals (Figure 1). Known excursions are generally associated with the next lowest intensities. Possible excursions seem to be intriguingly associated with less marked intensity minima. Further work is needed to verify this observation and to validate the "possible" excursions (red arrows; Figure 1). Some major paleointensity minima are not associated with known excursions. This could be because there was no excursion or because excursions were smoothed out of the sedimentary record or because detailed work has yet to identify or validate excursions in these time intervals. The geomagnetic field is dynamic with constantly changing paleointensity and abundant collapses (Figure 1), when excursions are more likely to occur. It is now clear that excursions are an intrinsic and frequent component of field behavior. A high quality excursion catalog is likely to grow as detailed studies are performed for time intervals older than the most recent excursions.

2.3. What is the Duration of an Excursion?

[6] The duration of geomagnetic excursions is relatively poorly known. Estimates range from 300 yr [*Thouveny and Creer*, 1992] to 1–2 kyr [*Laj et al.*, 2000, 2006; *Wagner et al.*, 2000; *Lund et al.*, 2001] to 3 kyr [*Channell*, 1999] to 8 kyr [*Channell*, 2006; *Knudsen et al.*, 2007] to 10 kyr [*Nowaczyk and Antonow*, 1997]. Longer durations estimated from the Arctic [*Nowaczyk and Antonow*, 1997] could reflect sedimentation rate fluctuations that cannot be resolved with available age models, and exemplify why estimating excursion duration is so difficult. High-resolution $\delta^{18}O$ data often provide age tie points to within an individual orbital precession cycle, but determining excursion duration requires interpolation between tie points assuming constant sedimentation. Variable sedimentation and chronological imprecision contribute to the wide range of estimates. Alternative methods are needed to precisely address this key question. *Knudsen et al.* [2007] measured the flux of excess ^{230}Th to the seafloor to reconstruct sedimentation rate variations between age tie points and estimated an 8 kyr duration for the Iceland Basin excursion at Ocean Drilling Program (ODP) Site 1063. However, these Bermuda Rise sediments lack a $\delta^{18}O$ chronology and dating of this stratigraphic interval is ambiguous [*Grützner et al.*, 2002]. This ambiguity raises concerns about the robustness of the duration estimate. Nevertheless, the excess ^{230}Th approach

could be useful for refining excursion duration estimates. The most robust estimate of excursion duration is probably from a Greenland ice core. Geomagnetic field intensity modulates cosmogenic radionuclide production, with production rate varying inversely with field strength. Peaks in ^{36}Cl production from the GRIP ice core provide a precise independent measure of the timing and duration of periods of weak field intensity associated with the Mono Lake and Laschamp excursions [*Wagner et al.*, 2000]. The annually layer-counted chronology has a resolution of 60 years for this interval of the ice core: major ^{36}Cl peaks confirm that the excursions occurred at the expected times and indicate a duration of ~1200 and 2500 years for the Mono Lake and Laschamp excursions, respectively [*Wagner et al.*, 2000]. These values provide the most precise current estimate of excursion duration and are shorter than the 7,000-year average global duration estimated for full polarity reversals [*Clement*, 2004]. Estimates of excursion duration from paleomagnetically well-resolved excursion records are insufficiently precise to test whether there is a latitude dependence of excursion duration, as was suggested by *Clement* [2004] to exist for full polarity reversals.

2.4. Why are Excursions not Always Recorded?

[7] The absence of recorded excursions in many high-resolution sedimentary paleomagnetic studies probably results from smoothing associated with post-depositional remanent magnetization (PDRM) acquisition. ''Best-case'' PDRM recording was modeled by *Roberts and Winklhofer* [2004] with lock-in a few cm below the bioturbated surface mixed layer. Sediments deposited at rates of 1–3 cm/kyr failed to record excursions despite an input signal containing abundant excursions with 1-kyr durations. Longer excursion durations increase the likelihood that excursions will be recorded. Excursion duration is not precisely known, therefore *Roberts and Winklhofer* [2004] presented nomograms for recording fidelity using two variables: excursion duration and sedimentation rate. They suggest that to consistently detect excursions, and to recover details of field behavior, minimum sedimentation rates should exceed 10 cm/kyr. The ''stop-and-go'' behavior observed in the ultra-highly-resolved Steens Mountain volcanic polarity transition record [*Mankinen et al.*, 1985] is only observed in exceptionally rapidly deposited sediments [e.g., *Channell and Lehman*, 1997; *Roberts et al.*, 2007]. This suggests that PDRM smoothing is fundamentally important in studies of field behavior from sediments.

2.5. Are Excursions Global in Scale?

[8] It has been argued that excursions are regional rather than global features [e.g., *Merrill and McFadden*, 2005]. The best-studied excursions have now been demonstrated to have global distribution. Inadequate paleomagnetic recording of short duration field behavior is therefore a more likely cause of sporadic excursion recording [e.g., *Roberts and Winklhofer*, 2004]. The Laschamp excursion is recorded in sediments and volcanic rocks in both hemispheres (Figure 2) [e.g., *Guillou et al.*, 2004; *Lund et al.*, 2005; *Laj et al.*, 2006; *Channell*, 2006; *Plenier et al.*, 2007; *Cassata et al.*, 2008]. Likewise, the Iceland Basin and other excursions are widely recorded in both hemispheres (see *Laj and Channell* [2007] for details). Cosmogenic isotope data from ice cores also provide convincing evidence for the global scale of excursions. Geomagnetic shielding of cosmic rays that produce these isotopes occurs in space at a distance of several Earth radii, where only dipolar geomagnetic components are significant. High cosmogenic nuclide flux during excursions [*Wagner et al.*, 2000] demonstrates that they are global phenomena involving large-scale dipole intensity reduction [*Laj and Channell*, 2007].

2.6. Is There Characteristic Field Behavior During Excursions?

2.6.1. Testable Hypotheses

[9] There are three main explanations for geomagnetic excursions [*Merrill and McFadden*, 1994]. In the first hypothesis, excursions have a global manifestation related to a significant departure of the dipole field from Earth's rotation axis. VGPs would therefore follow consistent paths for any given excursion. In the second hypothesis, a global manifestation is expected if the non-dipole to dipole field ratio becomes large, in which case VGP paths and the apparent polarity could vary around the globe. In the third hypothesis, relatively localized perturbations in Earth's outer core could give rise to excursions of restricted geographic extent associated with a large non-dipole field without any dipole reversal. High-quality, high-resolution data with precise chronological control are needed from widely distributed localities to distinguish among, and test, these hypotheses. In practice, lava flows, which are ideal paleomagnetic recorders, usually erupt too infrequently to provide high-resolution records. Likewise, at low sedimentation rates, excursions can be filtered out of sediment records [*Roberts and Winklhofer*, 2004]. The fundamental hindrance to understanding excursional fields therefore relates to data quality.

2.6.2. Simple Excursional Field Behavior?

[10] A useful test of excursional field behavior was recently made from multiple records of the two best-studied excursions [*Laj et al.*, 2006]. Seven detailed sedimentary records of the Laschamp (separated by 178° of longitude and 113° of latitude) and Iceland Basin excursions (separated by 165° and 41°, respectively) were analysed (Figure 2). The Laschamp records include those of *Lund et al.* [2005] and the Iceland Basin records include those of *Channell* [1999] and *Oda et al.* [2002]. VGP paths for the Iceland Basin excursion consistently loop counter-clockwise from high northern latitudes across Eurasia, through Africa to high southern latitudes, with a return through Australia and the western Pacific Ocean back to high northern latitudes (Figure 2b). Minor divergences from this overall pattern are attributed to noise or to variable PDRM smoothing. Some of the Laschamp records are probably affected by core disturbances and discontinuous sedimentation. Regardless, their VGP paths follow the same restricted geographical bands as the Iceland Basin excursion, except that they loop clockwise (Figure 2a). *Laj et al.* [2006] concluded that the consistency of these high-resolution records suggests a relatively simple, possibly dominantly dipolar, excursion field geometry, with similar dynamo mechanisms for both excursions. This might result from lower mantle control because of the short time constants of field generation in the outer core. The analysis of *Laj et al.* [2006] favors the first

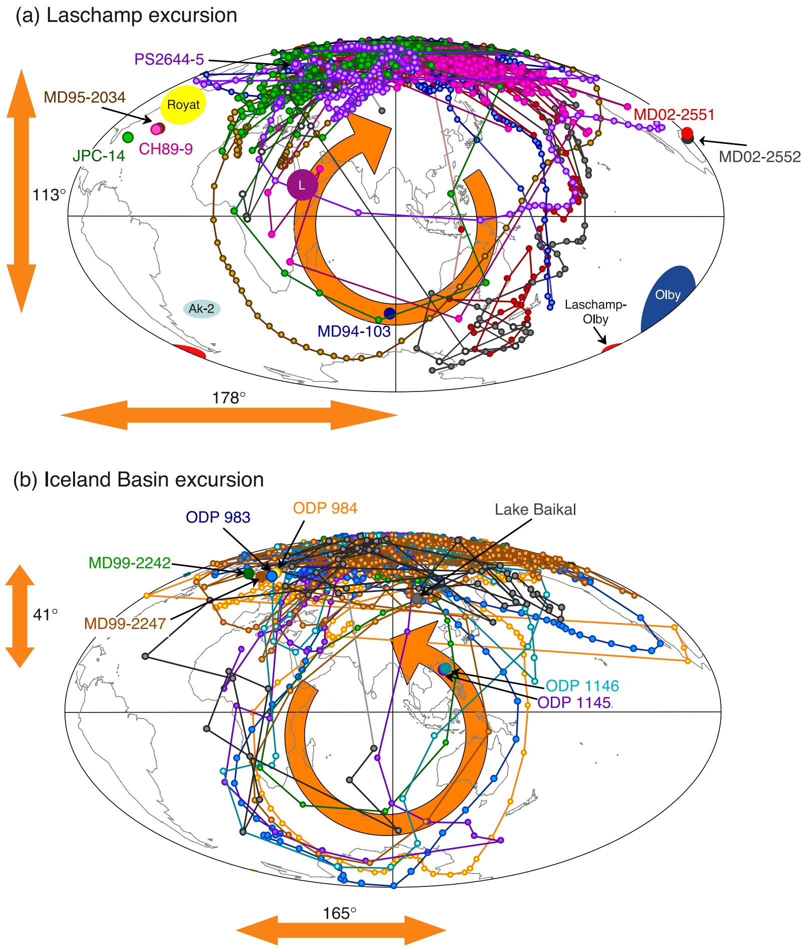

Figure 2. VGP paths (colour coded according to the site label for each respective sediment core with the overall pattern summarized by the orange loops) for the (a) Laschamp and (b) Iceland Basin excursions (from *Laj et al.* [2006]). Volcanic VGPs are shown for comparison for the Laschamp excursion at Laschamp-Olby (red cluster) [*Guillou et al.*, 2004], Olby (dark blue), Royat (yellow), Louchadière (purple) [*Plenier et al.*, 2007], and McLennan Hills, Auckland volcanic field, New Zealand (light blue) [*Mochizuki et al.*, 2006], which is Auckland cluster 2 of *Cassata et al.* [2008].

hypothesis of *Merrill and McFadden* [1994] concerning excursional field behavior.

2.6.3. More Complicated Excursional Field Behavior?

[11] The relative simplicity of excursional field behavior suggested by *Laj et al.* [2006] is a useful starting point for further tests. Alternative possibilities are already evident. The Laschamp excursion can only be confidently associated with volcanic rocks from two well-dated localities [*Cassata et al.*, 2008]; other volcanic records that have been associated with the Laschamp excursion are not considered here. The most recent published VGP data from Laschamp-Olby-Louchadière-Royat [*Guillou et al.*, 2004; *Plenier et al.*, 2007] are shown in Figure 2a along with data from McLennan Hills, Auckland, New Zealand [*Mochizuki et al.*, 2006]. Precise $^{40}Ar/^{39}Ar$ dates (39.1 ± 4.1 ka) indicate that the Auckland volcanics record the Laschamp excursion [*Cassata et al.*, 2008]. The respective VGPs are geographically restricted, as expected for spot readings of the field, but most do not lie close to the clockwise VGP loop of *Laj et al.* [2006]. Furthermore, the clockwise looping Laschamp VGP path from ODP Site 919 [*Channell*, 2006] does not fall on exactly the same longitudes as the loop in Figure 2a. These results were interpreted by *Plenier et al.* [2007] and *Cassata et al.* [2008] to indicate that the field during the Laschamp excursion was more complex than suggested by *Laj et al.* [2006].

[12] The Iceland Basin excursion compilation of *Laj et al.* [2006] lacks representation from the Pacific and southern hemispheres. *Laj et al.* [2006] presented a North Pacific record from ODP Site 884, which was not included in their final analysis, but that has been interpreted to represent the Iceland Basin excursion [*Roberts et al.*, 1997]. Four consistent, parallel excursion records (Figures 3a and 3b) can be inter-correlated and transferred to depths in Hole 884D using magnetic susceptibility data. Smoothed U-channel VGP data from Hole 884D are plotted in Figure 3d. *Laj et al.* [2006] did not include this VGP path in their compilation because Site 884 has no $\delta^{18}O$ record, and it is therefore only indirectly dated. In developing a 200-kyr North Pacific relative paleointensity stack, *Roberts et al.* [1997] used a low-resolution $\delta^{18}O$ record from nearby ODP Site 883 and correlated the 883 and 884 records using

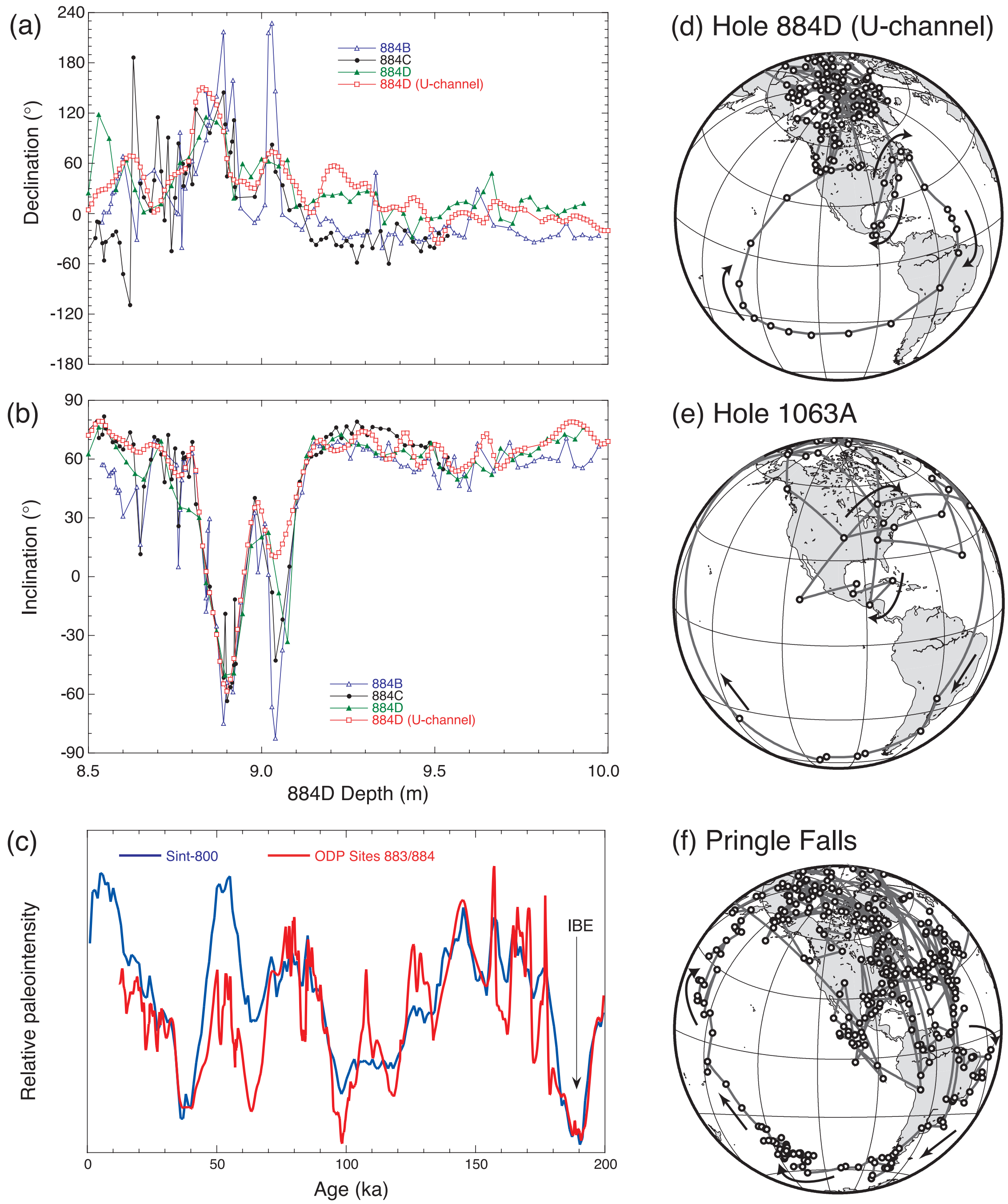

Figure 3. Paleomagnetic (a) declination and (b) inclination (characteristic remanent magnetization directions obtained after detailed stepwise alternating field demagnetization) for 4 parallel records of the Iceland Basin excursion from North Pacific ODP Holes 884B, C, and D (discrete and U-channel samples). (c) Stacked relative paleointensity record from ODP Sites 883 and 884 (red curve from *Roberts et al.* [1997]) correlated with the Sint-800 global paleointensity stack (blue) of *Guyodo and Valet* [1999]. The Iceland Basin excursion (IBE) occurs at the ~190 kyr minimum. (d) IBE VGP path from the smoothed Hole 884D U-channel record. This VGP path contrasts with IBE paths in Figure 2b [*Laj et al.*, 2006], but compares well with (e) the putative IBE record from ODP Hole 1063A [*Knudsen et al.*, 2006] and (f) the Pringle Falls type locality VGP path [*Herrerro-Bervera et al.*, 1994].

magnetic susceptibility variations. Crucially, the δ^{18}O chronology is poorly resolved near the marine oxygen isotope (MIS) stage 7/6 boundary, where the Iceland Basin excursion occurs. Nevertheless, the ODP 883/884 paleointensity record (Figure 3c) correlates well with the global Sint-800 stack of *Guyodo and Valet* [1999]. The excursion (Figures 3a and 3b) coincides with the paleointensity minimum at ~190 ka (Figure 3c). The lowermost MIS 6 δ^{18}O data point occurs at a depth of 8.90 m in Hole 883D, which is only 11 cm above the paleointensity minimum at 9.01 m. It is therefore reasonable to interpret the recorded excursion as the Iceland Basin excursion rather than as an earlier MIS 7 event such as the Pringle Falls excursion at 211 kyr [*Singer et al.*, 2008a] (although the similarity with the Pringle Falls VGP path of *Herrero-Bervera et al.* [1994] makes this proposition appealing (Figure 3f)). This suggests that the Iceland Basin excursion might have had more complex field behavior than indicated by *Laj et al.* [2006]. This possibility is supported by a high-resolution, high-latitude record from ODP Site 919 [*Channell*, 2006], which contains multiple rapid directional swings rather than a single or double VGP loop. *Laj and Channell* [2007] attributed discrepancies between this and other Iceland Basin excursion records to two possible factors: unrecognized sediment deformation in Hole 919A, or complex high latitude field behavior. These explanations might be valid, but the possibility of more complicated excursional field behavior should also be considered.

[13] Of the 12 Brunhes Chron excursions reported by *Lund et al.* [2001], excursion 7α was interpreted to represent the Iceland Basin excursion. The respective VGP path from ODP Hole 1063A [*Knudsen et al.*, 2006] (Figure 3e) is similar to both the Hole 884D (Figure 3d) and Pringle Falls records (Figure 3f). It contains a small clockwise loop over central America before returning to high northern latitudes and then looping clockwise through South America to high southern latitudes and back to high northern latitudes through the western Pacific. The similarity between VGP paths from ODP sites 1063 and 884 could indicate that the Iceland Basin excursion has a second type of VGP path that would require a higher-order, non-dipole field configuration (although the field could still have had a relatively simple geometry). However, doubts exist about the chronology of ODP Site 1063, which lacks a δ^{18}O record. For Site 1063, *Grützner et al.* [2002] tuned carbonate variations to astronomical target curves and concluded that: "...weak precession-related cycles were found in MIS 6 and 7. This made precession tuning very difficult in this interval because time shifts of 20 kyr resulted in very similar filter outputs and made the correlation ambiguous." This example illustrates the unavoidable ambiguities that exist without a continuous high-precision chronology. High-quality chronological and paleomagnetic data are both required to understand excursional fields. Data shown in Figure 3 might indicate more complex excursional field behavior than suggested by *Laj et al.* [2006], but further detailed records with precise dating are needed to rigorously confirm this possibility.

3. Future Directions for Geomagnetic Excursion Research

[14] Increasingly routine high-resolution paleomagnetic and δ^{18}O analysis of rapidly deposited marine sediments and high-precision radioisotopic dating of excursions from volcanic rocks are providing a significant knowledge expansion for an important aspect of geomagnetic field behavior. Further research should focus on the following areas to resolve major unanswered questions concerning excursions. These requirements are: (1) improving the global distribution of excursion records, particularly from the southern hemisphere; (2) obtaining high-resolution sedimentary excursion records with good age control from sites with sedimentation rates >10 cm/kyr; (3) obtaining volcanic excursion records coupled with high-precision geochronology; and (4) estimating excursion duration with high chronological precision. These efforts will enable testing of hypotheses concerning the deep earth dynamics that generate excursions.

4. Conclusions

[15] Major advances in geomagnetic excursion research have begun to answer fundamental questions over the last decade. Excursions are now recognised as relatively common phenomena associated with field intensity minima. Excursions are inferred to occur when the field reverses polarity in Earth's outer core, but not in the inner core (which takes longer to occur). A strong case has been made for dominantly dipolar field behavior during two well-studied excursions. However, this has been contested and detailed, globally distributed, records are needed to settle the debate. Recent advances provide an excellent platform for addressing key questions concerning the frequency, duration, and style of field behavior associated with excursions.

[16] **Acknowledgments.** I thank the *GRL* editors for inviting me to write this paper and John Geissman and Toshi Yamazaki for helpful review comments. Antony Pout and Matt O'Regan helped to acquire data shown in Figures 3a and 3b. Emilio Herrero-Bervera kindly provided data shown in Figure 3f.

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