



Geomagnetic field behavior during the Iceland Basin and Laschamp geomagnetic excursions: A simple transitional field geometry?

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[1] We present four new records of the Iceland Basin Excursion (IBE) and five new records of the Laschamp Excursion (LE) obtained from rapidly deposited marine sediments in the North Atlantic Ocean, the Nordic Seas, the Gulf of Mexico, the South China Sea, and the southern Indian Ocean. Marked minima in relative paleointensity correspond with the paleomagnetic directional changes associated with all of the excursion records. The virtual geomagnetic pole (VGP) paths of the four IBE records are all similar. The VGPs move southward over Europe and Africa, reaching the southern hemisphere (three reach Antarctica), and then move to more eastern longitudes before returning northward over Australia and east Asia, describing a large counterclockwise loop. The same VGP pattern is observed in other published records. The VGP paths observed for the LE are similar to those of the IBE; however, they loop clockwise instead of counterclockwise. Despite the different sense of looping, the marked similarity among the paths for the two excursions suggests that a similar, relatively simple geometry dominated the transitional field during both the IBE and the LE. Similar dynamo mechanisms must therefore have been active in the Earth's core for both excursions. The duration of the excursions is estimated at <2,000 years, which supports the suggestion that a difference exists between the mechanisms for excursions and reversals. However, the coincidence of the longitudinal bands for VGPs associated with excursions compared to some reversal paths could also indicate an inherent link between the mechanisms for reversals and excursions.

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1. Introduction

[2] Many records of geomagnetic field behavior during polarity reversals have been acquired in recent years and have given rise to an unresolved

controversy. The first compilations of virtual geomagnetic pole (VGP) paths during reversals suggested that they would preferentially lie within longitudinal bands through the Americas and east Asia [Clement, 1991; Laj et al., 1991]; these

regions coincide with lower mantle heterogeneities that could have induced persistent flow patterns in the Earth's outer core [Laj *et al.*, 1991]. However, it was also suggested that the VGP paths appeared to lie 90° away from their respective site longitudes, which, if true, would suggest possible artifacts in sedimentary recording of the geomagnetic field [Langereis *et al.*, 1992; Valet *et al.*, 1992; McFadden *et al.*, 1993]. No clear answer has yet been developed for this important issue, but it has stimulated wide interest and a large number of studies.

[3] It was not initially realized that excursions might have a different nature to reversals, so their VGP paths have often been considered together with reversal paths when statistically testing the hypothesis of preferential bands for transitional VGP paths [Laj *et al.*, 1991; McFadden *et al.*, 1993]. It has, however, been suggested that excursions might occur when the field reverses in the Earth's liquid outer core, which has timescales of the order of 500 years or so, whereas full geomagnetic reversals can only occur when the field in the solid inner core reverses polarity, which occurs by diffusion on timescales of ~3 kyr [Gubbins, 1999]. Excursions therefore have the potential for exploring the complex mechanisms associated with the geomagnetic dynamo, alongside the study of reversals.

[4] The study of geomagnetic excursions has progressed relatively slowly for several reasons. It is difficult to locate and detect such relatively short events in volcanic sequences due to the normally low eruption frequency of volcanoes and because such short-lived phenomena can be easily smoothed out of the record in relatively slowly deposited sediments [cf. Roberts and Winkhofer, 2004]. There are also difficulties in precisely correlating excursions at distant sites, which can make it difficult to assess whether two excursion records are coeval. Consequently, the few existing studies of vector changes of the field during excursions do not provide sufficiently large geographic coverage of sampling sites to adequately constrain the geometry of the transitional field. Many more well dated records are needed for most excursions to address the nature of the geomagnetic field during excursions.

[5] We report here new data (directions and relative intensity changes) for the Iceland Basin excursion (IBE) and for the Laschamp excursion (LE). These new data were obtained from four marine cores from the North Atlantic Ocean and the South

China Sea for the IBE and from five new records for the LE from the North Atlantic Ocean and Nordic Seas, the Gulf of Mexico and the southern Indian Ocean. When combined with published data for the same excursions, the broad geographic coverage of available records allows us to suggest that a simple geometry may have characterized the geomagnetic field during these two excursions.

2. Core Locations, Sampling, and Laboratory Methods

[6] Two of the four new records reported here for the IBE originate from the North Atlantic Ocean at different locations from the Ocean Drilling Program (ODP) sites for which this excursion is named [Channell *et al.*, 1997; Channell, 1999]. This extends the geographical sampling area for the IBE in the North Atlantic Ocean. The two cores were collected during the GINNA IMAGES cruise of the *Marion Dufresne* of the French Polar Institute, one of which (MD99-2242) lies on the Eirik Drift, south of Greenland, while the second (MD99-2247) is from the western flank of the Reykjanes Ridge. The two other records were obtained from the South China Sea at ODP sites 1145 and 1146 that were cored during ODP Leg 184. A common characteristic of the four sites is the relatively high sediment accumulation rates, which varied from 7 to 15 cm/kyr, as evaluated from oxygen isotope studies conducted on the respective cores (see below), which were interpreted using the orbitally tuned SPECMAP timescale [Bassinot *et al.*, 1994]. These sedimentation rates lie within the range required for adequate recording of excursions in environments with shallow remanence lock-in, as predicted by Roberts and Winkhofer [2004].

[7] The five new records presented here for the LE were obtained from core MD95-2034 from the Bermuda Rise (IMAGES cruise MD-101), core PS2644-5 from a cruise of the *Polar Stern* northwest of Iceland, cores MD02-2251 and MD02-2252 from the Orca Basin of the Gulf of Mexico during the PAGE IMAGES cruise of the *Marion Dufresne*, and from core MD94-103 from the southern Indian Ocean during the PACIMA cruise of the *Marion Dufresne*.

[8] Core locations are shown in Figure 1 and coordinates of the cores and the water depths at which they were recovered are presented in Table 1. The locations of the cores studied by other authors and discussed here are also indicated in

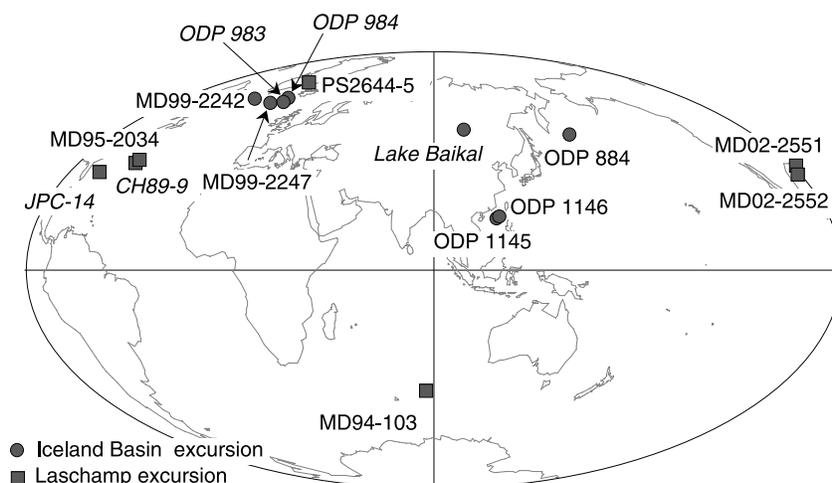


Figure 1. Map of core locations of excursion records considered in this paper. Squares (circles) are for the cores in which the Laschamp excursion (Iceland Basin excursion) was studied. Cores labeled in italics represent excursion records reported in the literature. Coordinates of the studied cores are reported in Table 1.

Figure 1 and Table 1. There is a 10–40° latitude difference and about a 160° difference in longitude among the cores sampled for the IBE, and a difference of roughly 112° in latitude and 150° in longitude among those used to study the LE.

[9] U-channel samples were collected for paleomagnetic analysis by pushing rigid u-shaped plastic liners (2 × 2 cm square cross-section and 1.5 m in length) into the working halves of the cores. The Orca Basin is characterized by sedimentation rates that vary significantly on short timescales, in particular during the LE. In order to improve the resolution in intervals where the sedimentation rate was low, we also sampled additional 1-cm slices

from core MD02-2552. Core MD94-103 had no suitable sediment remaining for such detailed directional analyses. Small amounts (0.3–0.5 g) of sediment were taken at regular intervals in all of the cores for magnetic hysteresis and thermomagnetic analyses.

[10] Measurements of the remanent magnetization were made at 2-cm intervals with a 2-G Enterprises model 755-R cryogenic magnetometer that is housed in the mu-metal shielded room at the LSCE. The spatial resolution of the pick-up coils is about 4 cm, so only one out of two measurements is independent and there is some smoothing of the signal [Weeks *et al.*, 1993]. The standard

Table 1. Coordinates and Water Depths of the Studied Cores for Each Excursion Record

Core	Latitude	Longitude	Water Depth, m	Reference
<i>Iceland Basin Excursion</i>				
MD99-2242	58°55.06'N	047°07.49'W	2895	this study
MD99-2247	59°04.61'N	031°28.34'W	1690	this study
ODP Site 1146	19°27.40'N	116°16.37'E	2092	this study
ODP Site 1145	19°35.04'N	117°37.86'E	3175	this study
ODP Site 884	51°27.02'N	168°20.23'E	3826	this study
ODP Site 983	60°24.21'N	023°38.44'W	1983	Channell <i>et al.</i> [1997]
ODP Site 984	61°25.51'N	024°04.94'W	1648	Channell [1999]
Lake Baikal (Ver98-1)	53°41.65'N	108°21.01'E	335	Oda <i>et al.</i> [2002]
<i>Laschamp Excursion</i>				
MD95-2034	33°41.40'N	057°34.55'W	4460	this study
MD02-2251	26°56.78'N	091°20.75'W	2255	this study
MD02-2252	26°53.80'N	091°20.72'W	2240	this study
MD94-103	45°35.00'S	086°32.00'E	3559	this study
PS2644-5	67°52.02'N	021°45.92'W	777	this study
JPC-14	28°36.00'N	073°06.00'W	—	Lund <i>et al.</i> [2005]
CH89-9	33°42.00'N	057°36.00'W	—	Lund <i>et al.</i> [2005]

measurement routine comprised stepwise alternating field (AF) demagnetization of the natural remanent magnetization (NRM) in 10 to 13 steps from 0 to 60 mT or to 70 mT, beyond which the noise level of the magnetometer was reached and erratic results were obtained. The directional stability of the paleomagnetic vector was assessed during demagnetization by generating demagnetization plots at 2-cm stratigraphic intervals. The same demagnetization procedure for the NRM was applied to discrete samples (1-cm slices) taken through the final part of the excursion in core MD02-2552.

[11] An anhysteretic remanent magnetization (ARM) was imparted using a 100 mT AF and a 0.05 mT bias field. The ARM was then measured and stepwise demagnetized using the same steps as for the NRM. The translation speed of the u-channels during acquisition of ARM was 1 cm/sec and 4 cm/sec during demagnetization of NRM and ARM. Translation speeds higher than these values can lead to incomplete acquisition of ARM and incomplete demagnetization of the NRM and ARM [Sagnotti *et al.*, 2003; Brachfeld *et al.*, 2004].

[12] The isothermal remanent magnetization (IRM) was imparted in six steps up to 1 T using a 2-G Enterprises pulse magnetizer (solenoid) that is arranged in-line with a 2-G Enterprises cryogenic magnetometer with RF-SQUIDS. At each acquisition step, two successive pulses were applied. After imparting an IRM at 1 T, a reverse field of 0.3 T was applied and the magnetization was measured in order to allow calculation of the S-ratio (where $S\text{-ratio} = -\text{IRM}_{-0.3\text{T}}/\text{IRM}_{1\text{T}}$ [King and Channell, 1991]).

[13] Although the low-field volume magnetic susceptibility (κ) was measured on board the research vessels during the respective cruises, measurements were repeated in the magnetically calmer environment of our laboratory. U-channel samples were systematically used and measurements were made at 2-cm intervals, using a horizontal translation system. The Bartington Instruments sensing coil used in our laboratory has a spatial resolution that is similar to that of the cryogenic magnetometer.

[14] Magnetic hysteresis measurements of small sediment samples (5–10 mg) were performed using an alternating gradient magnetometer (Princeton Measurements Corporation AGM 2900). Variations in the grain size of the magnetic

minerals were investigated by plotting the ratio of ARM to the low-field magnetic susceptibility [Banerjee *et al.*, 1981] and the ratio of the remanent magnetization to the saturation magnetization (M_r/M_s) versus the ratio of the coercivity of remanence to the coercive force (H_{cr}/H_c) [Day *et al.*, 1977].

[15] Thermomagnetic analyses were made in an argon atmosphere for selected samples using a horizontal Curie balance. In cores from the South China Sea, where the magnetic mineral contents were too low for Curie balance analysis, we investigated the nature of the magnetic minerals by studying the thermal decay of a composite IRM using the method of Lowrie [1990].

3. Results

3.1. Core Stratigraphy and Identification of the Excursions

[16] In each studied core, the excursions were clearly identified by a large paleomagnetic directional change associated with a relative paleointensity minimum (see below). The stratigraphy of the cores in which we identified the IBE is based either on planktic (MD99-2242 (C. Hillaire-Marcel, personal communication, 2004), MD99-2247 (E. Cortijo, personal communication, 2001) and Site 1145 (K. McIntyre and D. Oppo, personal communication, 2003)) or benthic oxygen isotope records (Site 1146 [Clemens and Prell, 2003]). The records from the North Atlantic Ocean, according to the orbitally tuned SPECMAP timescale [Bassinot *et al.*, 1994], place the IBE at the transition between marine isotope stage (MIS) 7 and 6, which is dated at about 185 ka [cf. Channell *et al.*, 1997; Channell, 1999]. Average sedimentation rates during the excursion ranged from 7 to 10 cm/kyr for all of the studied cores. In the South China Sea, the planktic oxygen isotope records at the two ODP sites have considerable environmental variations associated with monsoon dynamics [Clemens and Prell, 2003]. Therefore, at both sites, the age model was based on the benthic record from Site 1146 [Clemens and Prell, 2003] that we transferred to Site 1145 by correlating between the two planktic records. At the two sites, the average sedimentation rate was about 15 cm/kyr and the excursion is located precisely at the boundary between MIS 7 and 6.

[17] The LE is located within MIS 3, which puts it within reach of radiocarbon dating. In addition, in

areas where rapid climatic changes associated with the Dansgaard-Oeschger cycles [Dansgaard *et al.*, 1993] are identified, it has been shown that the LE occurred during interstadial 10 [Baumgartner *et al.*, 1997; Laj *et al.*, 2000; Wagner *et al.*, 2000], at about 41 kyr in the age model for the GISP2 ice core. This age is consistent with recent radiometric dating of the excursions lava flow at the Laschamp locality [Guillou *et al.*, 2004]. Radiocarbon datings obtained for one core from the Orca basin (MD02-2551) are consistent with an age of about 40–41 kyr for the geomagnetic excursion recognized at about 27.5 m in this core [Hill *et al.*, 2004]. This age model has been transferred to the twin core MD02-2552 using the low-field magnetic susceptibility and grayscale reflectance as correlation parameters. In the North Atlantic Ocean and Nordic Seas, cores MD95-2034 and PS2644-5 both contributed to the NAPIS-75 paleointensity stack [Laj *et al.*, 2000]. In these cores, the LE is coeval with interstadial 10, which has been recognized using magnetic properties [Kissel *et al.*, 1999] and the carbonate content for core MD95-2034 [Adkins *et al.*, 1997]. A planktic oxygen isotope record for core MD94-103 from the Kerguelen Plateau (southern Indian Ocean) places the LE within MIS 3 and the age model could be refined by transferring the GISP2 age model using the correlation between NAPIS-75 and the paleointensity record from this core [Mazaud *et al.*, 2002]. In the following discussion, results from all cores will be reported versus age.

3.2. Natural Remanent Magnetization

[18] Representative NRM demagnetization data from both excursions are shown in Figure 2. Inclinations and declinations of the characteristic remanent magnetization (ChRM) were determined by principal component analysis using software developed by Mazaud [2005]. The software allows selection of the portion of the demagnetization diagram over which the ChRM is determined, which can differ from horizon to horizon. This allows separation of the ChRM from the coring-induced overprint in the ODP cores. The maximum angular deviation (MAD) never exceeds 2° for the Bermuda Rise core, 4° for the other North Atlantic cores, 8° for the Orca basin, the Iceland Sea (PS core) and ODP Site 1146, and 13° for Site 1145. At Site 1145, the highest MAD values (>10°) are observed only for five transitional directions associated with the weakest magnetizations. The MAD values are a little larger (up to 13°) for the 1-cm slices taken from core MD02-2552. The cores were

not oriented during recovery. We therefore obtained the paleomagnetic declinations by reorienting the cores so that the declinations from nonexcursion intervals averaged to 0°. Records of declination, inclination, MAD and NRM/ARM values are shown in Figures 3a and 3b.

3.3. Nature of the Magnetic Minerals

[19] The magnetic mineralogy of ODP Site 1146 and of cores MD95-2034, PS2644-5 and MD94-103 has already been investigated in detail [Kissel *et al.*, 1999, 2003; Laj *et al.*, 2000; Mazaud *et al.*, 2002]. The main magnetic mineral is fine-grained low-Ti magnetite, with a small amount of higher coercivity minerals during cold climatic stages at Site 1146. For the other cores, thermomagnetic analysis (or results of the Lowrie [1990] method) invariably reveals Curie temperatures in the range of 570–590°C, which is typical of magnetite (Figure 4). This is consistent with S-ratio values, which indicate the dominance of a low coercivity mineral (Figure 4). As is the case for Site 1146, cold stages are also characterized by the presence of small amounts of higher coercivity minerals at Site 1145. Also, ARM versus k diagrams (Figure 5) indicate that down-core changes in magnetite concentration never exceed a factor of 6 and that the magnetic grain size is uniform through the excursions, which is also confirmed by magnetic hysteresis results. All of the studied sediments therefore meet the selection criteria for reliable relative paleointensity determinations [Tauxe, 1993, and references therein].

3.4. Relative Paleointensity Records

[20] Records of relative paleointensity were generated using κ , ARM and IRM as normalizers for the NRM, after demagnetization of the respective remanent magnetizations in a 25 mT peak AF. Similar, often virtually identical, results were obtained with the three normalizers (Figure 6), which is a good indication that the sediments provide reliable relative paleointensity determinations [Tauxe, 1993]. Records of relative paleointensity using ARM as a normalizer are shown for all of the cores studied here in Figures 3a and 3b. There is a significant intensity minimum that coincides with the directional excursion in each record.

3.5. Virtual Geomagnetic Pole (VGP) Paths

[21] The VGP paths obtained in this study for the IBE and the LE are shown in Figure 7. The VGP

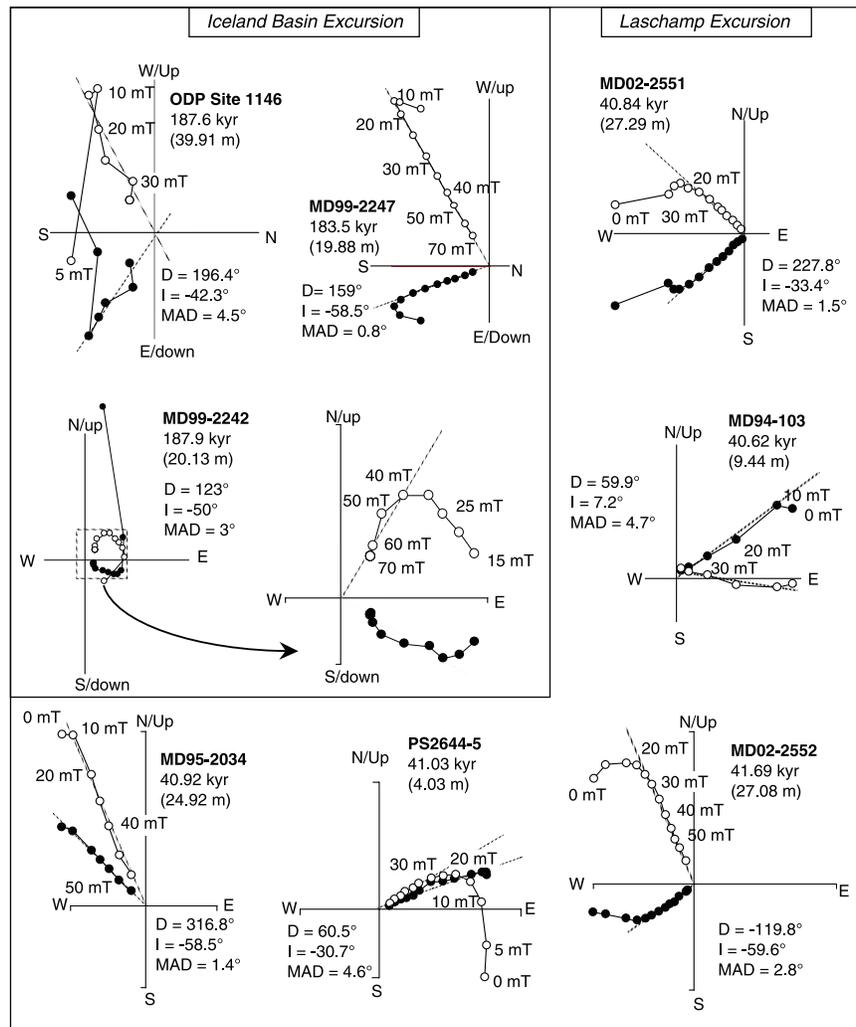


Figure 2. Representative demagnetization diagrams for the two studied excursions from different cores (the depth in the core and interpreted age are given underneath the name of the core). Black (white) circles represent projections onto the horizontal (vertical) plane. Shaded lines indicate the best fit line obtained using principal component analysis; the declination, inclination, and maximum angular deviation (MAD) value for each of these fits is stated for each diagram.

paths for the IBE are strikingly similar for the four cores from the North Atlantic to the South China Sea (Figure 7a). During the first part of the IBE, the VGPs remain at high northern latitudes and then move southward over Africa along a narrow band of longitudes before crossing the equator and reaching high southern latitudes (fully reversed polarity directions). The VGP path for core MD99-2242 is less well resolved, with poles crossing the southern Indian Ocean rather than reaching Antarctica. All of the VGPs then move back to the northern hemisphere within a longitudinal band over east Asia.

[22] A coherent picture is also observed for the LE (Figure 7b). For this excursion, the southward

directed part of the VGP paths first passes over east Asian/western Pacific longitudes and then reaches high southern latitudes. This is clear in all of the records. In core PS2644-5, this first part of the excursion is perturbed; the declinations are scattered, partly because of the high northern latitude of this coring site and also because a break between two core sections coincides with the beginning of the excursion. The edge effects inherent to u-channel measurement [e.g., Weeks *et al.*, 1993] make it impossible to correctly measure the first part of the excursion for this core. Unfortunately, the core could not be resampled with discrete samples, so the early part of the excursion remains poorly defined in this record. In records

Iceland Basin Excursion

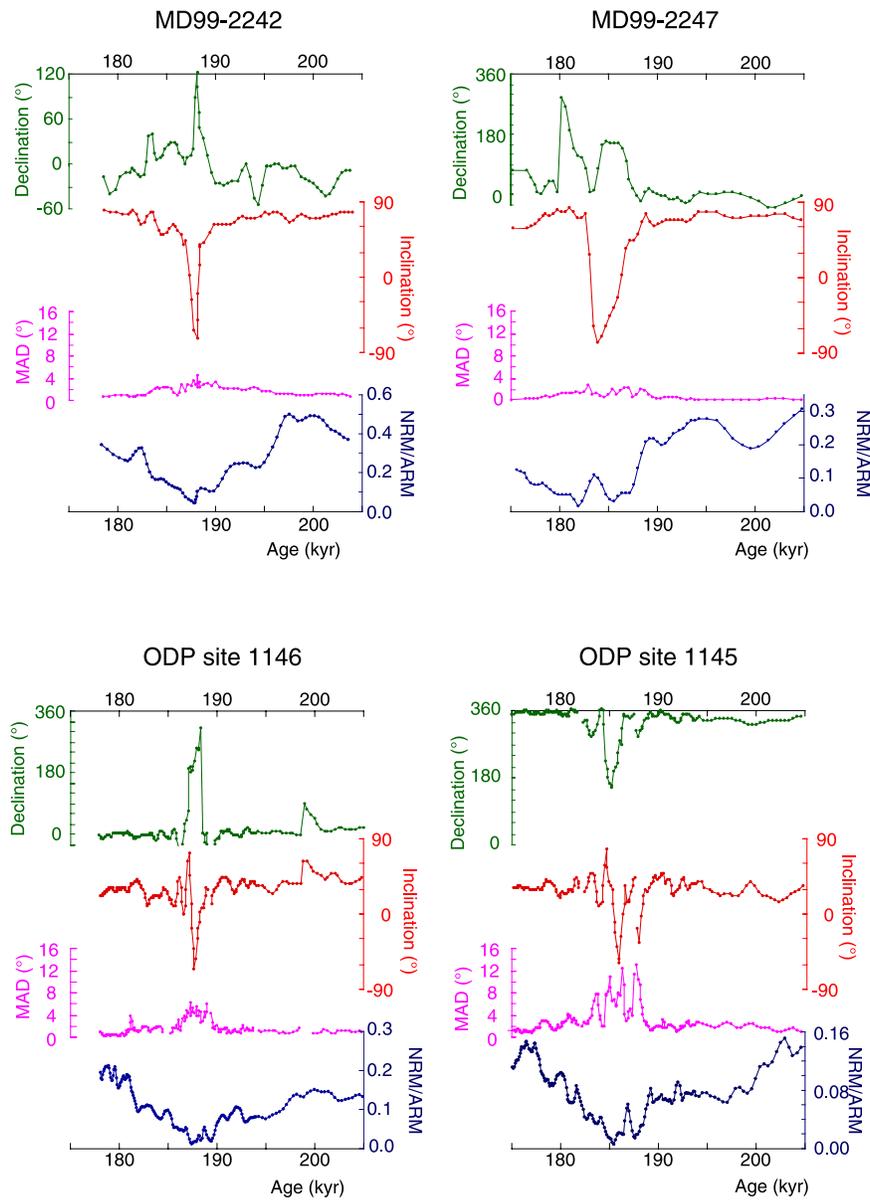


Figure 3a. Records of declination, inclination, maximum angular deviation (MAD), and normalized relative paleointensity (NRM/ARM) for the Iceland Basin excursion from the four studied sites.

where the later part of the excursion is well defined from the u-channel samples, as it is in cores MD95-2034 and PS2644-5, the northward directed part of the VGP path proceeds over Africa and western Europe. Low sedimentation rates during the second part of the excursion in both records from the Orca basin and in the record from the southern Indian Ocean mean that the return path is defined by only one or two points in the u-channel records. For core MD02-2552, the discrete 1-cm samples taken in this part of the core improve the resolution of the

return path. They yield intermediate VGPs first over northwestern Europe and then over north Africa. The clockwise looping path is similar in its geographical extent to those obtained from the other sites. For the LE as well as for the IBE, the turning point where the VGPs change from being southward to northward directed coincides with the minimum in relative paleointensity.

[23] All of the VGP paths for each excursion are superimposed in Figure 8. In addition, we also

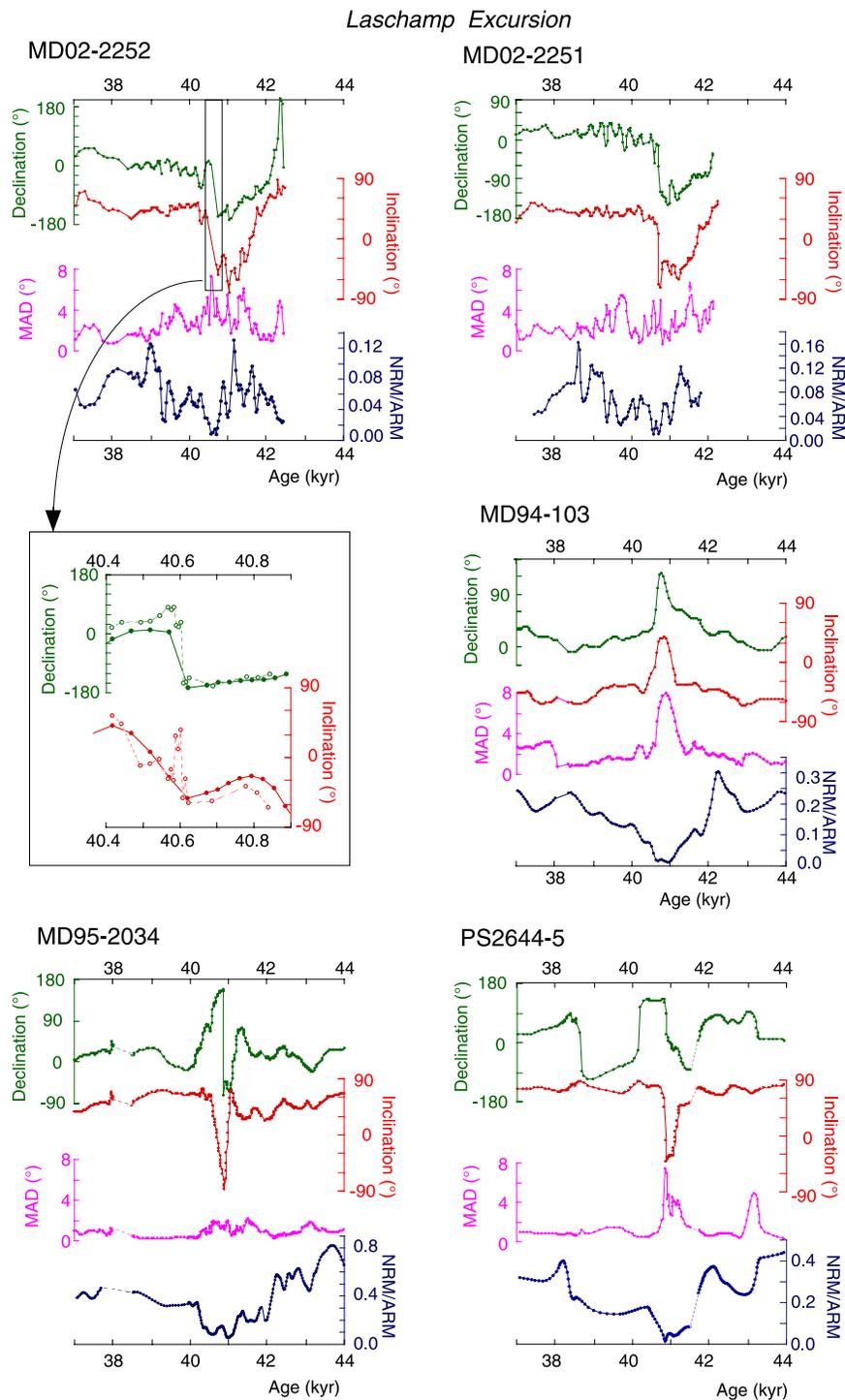


Figure 3b. The same data as shown in Figure 3a for the five studied records of the Laschamp excursion. An enlarged view of the declinations and inclinations is given for the final part of the excursion as recorded from both u-channel (solid symbols) and discrete samples (open symbols) for core MD02-2552.

show a selection of the records reported in the literature. This selection was made using the same strict standards of dating as those used for our records. The two records of *Lund et al.* [2005] have been unambiguously identified as the LE on the

basis of oxygen isotope stratigraphy. We also only consider records of the IBE that have been unambiguously tied to the MIS 7/6 transition: ODP sites 983 and 984 from the North Atlantic Ocean [*Channell et al.*, 1997; *Channell*, 1999] and the

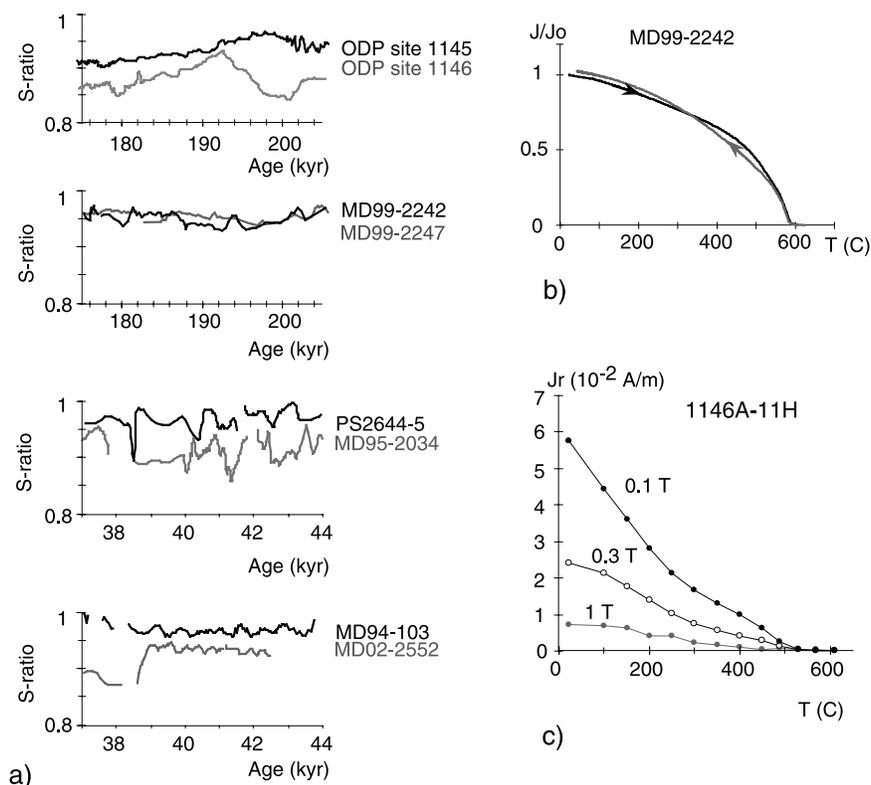


Figure 4. Representative mineral magnetic properties of the sediments from the excursions, as illustrated by (a) the S-ratio, (b) a thermomagnetic curve, and (c) a three-axis thermal demagnetization of an IRM following the method of Lowrie [1990].

record from Lake Baikal [Oda *et al.*, 2002] meet this strict dating requirement. This requirement leads to exclusion of lake sediment records from western North America [Liddicoat, 1990; Herrero-Bervera *et al.*, 1994; Negrini *et al.*, 1994], where available dating evidence is sufficiently ambiguous that the detailed excursion records could represent the IBE or an older excursion within MIS 7. Also, we have not considered records from the South Atlantic reported by Stoner *et al.* [2003] because the NRM does not appear to be sufficiently stable upon demagnetization, as recognized by the authors themselves. Likewise, other possible or probable records of the IBE are not considered here for a range of reasons. The transitional VGPs obtained by Nowaczyk and Baumann [1992], Yamazaki and Ioka [1994], Weeks *et al.* [1995], Lehman *et al.* [1996], and Nowaczyk and Antonow [1997] are not detailed enough, while Lund *et al.* [2001] have yet to publish their IBE records in sufficient detail for consideration here.

[24] For the IBE, the similarity of the different paths is clear when they are all displayed together (Figure 8a). The records from ODP sites 983 and 984 from the North Atlantic Ocean yield a detailed

picture of the VGPs during the entire excursion, which is entirely consistent with that of our records. The record from Lake Baikal is less detailed. During the first half of the excursion, the VGP path lies clearly over northern Europe and Africa, although with some scatter. The VGP path during the second half of the excursion is described by only three points. The general pattern, however, is clearly that of a large counterclockwise loop, which lies over the same regions as the more detailed records. Therefore, in all cases, the overall picture of the VGP paths for the IBE is that of a counterclockwise loop that passes southward over western Europe and Africa and northward over east Asian longitudes.

[25] For the Laschamp excursion, an opposite picture is systematically observed (Figure 8b), with the two records of Lund *et al.* [2005] confirming those reported here. The VGP paths first move southward over east Asian/western Pacific longitudes, reaching high southern latitudes in the Indian Ocean and returning over Africa and western Europe. All of the records are therefore characterized by a clockwise loop over similar longitudinal bands as those observed for the IBE.

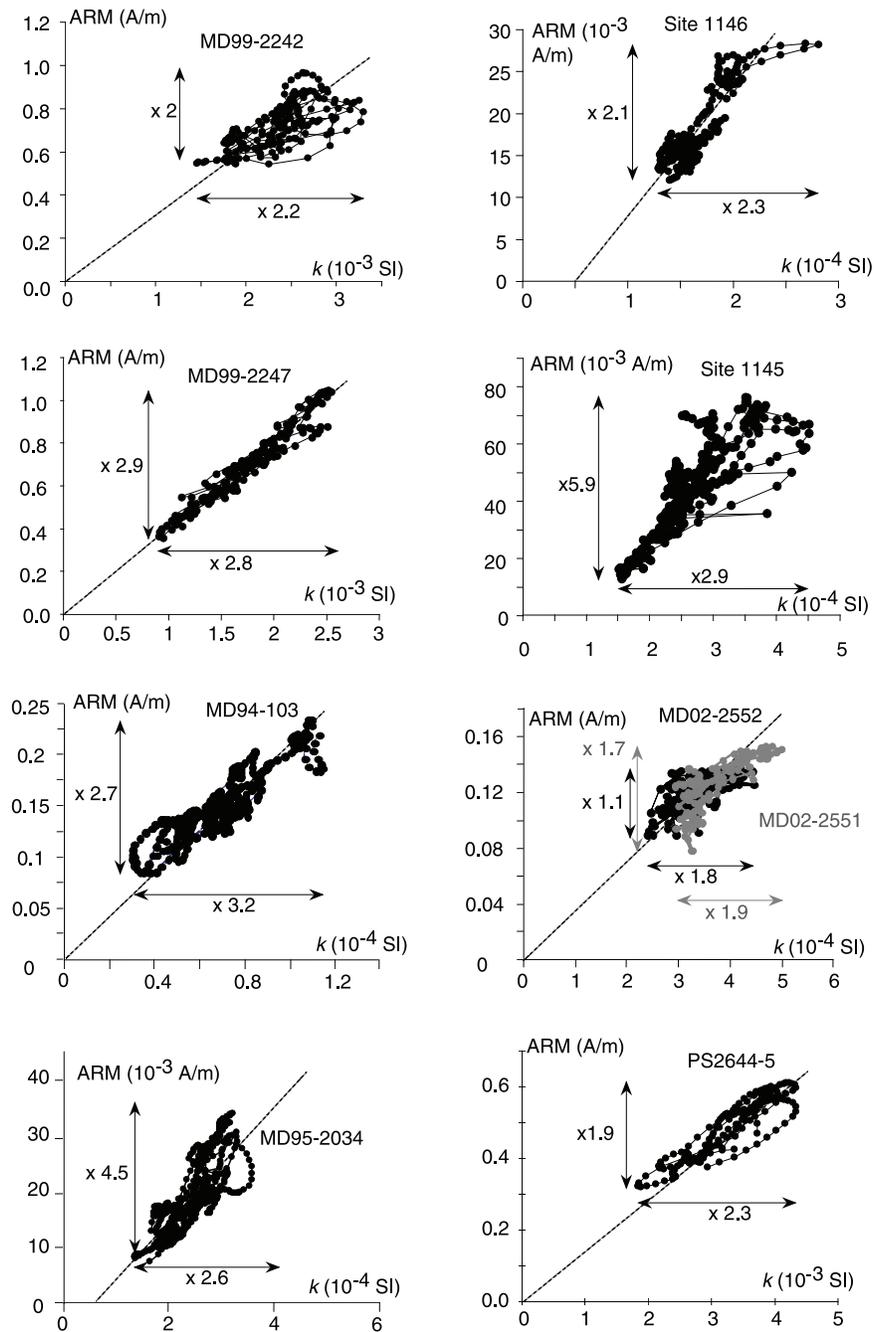


Figure 5. Grain sizes of magnetite, as illustrated by plots of ARM versus k [cf. Banerjee *et al.*, 1981], within the intervals spanned by the Iceland Basin and Laschamp excursions for all nine studied records. The factors by which the ARM and k vary are indicated by the arrows parallel to each axis. The amount by which these parameters vary is stated beside the arrows. All of these values fall within the limit of 10 stipulated by *Tauxe* [1993] as being suitable for relative paleointensity determinations.

[26] One of the main points considered in the controversy surrounding interpretation of VGP paths for geomagnetic reversals was the tendency for these paths to systematically lie 90° away from their respective site longitudes. It was suggested that this could arise from shallowing of inclinations

due to imperfect recording of the geomagnetic field by sediments during periods of low intensity, when gravitational forces might prevail over the aligning force of the geomagnetic field [McFadden *et al.*, 1993; Quidelleur and Valet, 1994]. Inclination shallowing is not observed here, as particularly

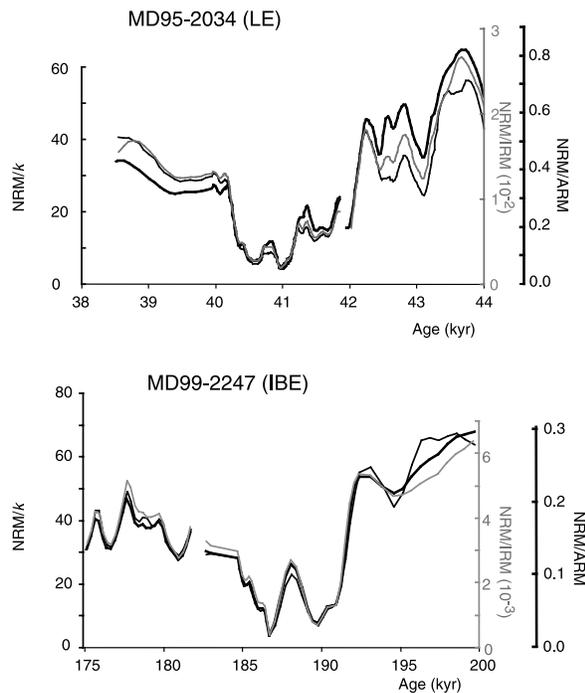


Figure 6. Comparison of relative paleointensity estimations obtained by normalizing the NRM with k , ARM, and IRM. One example is chosen for the Iceland Basin excursion (core MD99-2247), and one is chosen for the Laschamp excursion (MD95-2034). The close agreement among the three curves in both examples indicates that all three normalizers are suitable for relative paleointensity determination.

illustrated in the South China Sea records where steep inclinations are recorded during the low intensity excursions (Figures 3a and 3b). There is also no general tendency for these VGP paths to systematically lie 90° away from the respective site longitudes: the western European-African path (i.e., the normal to reverse part of the path for the IBE and the reverse to normal part for the Laschamp excursion) is situated roughly between 45° (ODP sites 983 and 984) and 110° (MD02 sites) of longitude away from the sites in the Atlantic Ocean and Gulf of Mexico, and at about 100° of longitude away from the sites in the South China Sea. The other path, over east Asia and the western Pacific, lies some 150° away from the Atlantic sites and 140° of longitude away from the sites in the Gulf of Mexico and 0° to 40° of longitude away from the South China Sea sites. Apart from the Orca Basin cores, where, because of the low sedimentation rate, analysis of u-channel samples has smoothed the second half of the excursion, this measurement technique does not appear to have significantly distorted the paleo-

magnetic signal. In the North Atlantic, for instance, records of the LE obtained with u-channels or with discrete samples display virtually identical inclination records [see Laj *et al.*, 2000, Figure 6b]. In addition, it has been shown that in the North Atlantic and Nordic Sea cores, that make up the NAPIS record, postdepositional remanence acquisition is negligible [Kissel *et al.*, 1999; Laj *et al.*, 2000]. The similarities among records from widely separated geographical areas indicate that significant delays in remanence acquisition are probably unlikely at the studied sites outside the North Atlantic. These observations indicate a shallow lock-in of the magnetization, and the high sedimentation rates place the respective records within the range expected for reliable recording of excursions within sediments with shallow remanence lock-in [Roberts and Winklhofer, 2004]. The studied sediments therefore appear to reliably record geomagnetic field changes even when the field had low intensities within the excursions.

[27] Roberts *et al.* [1997] documented an excursion in the North Pacific Ocean at ODP Site 884. Preservation of foraminifera was poor at this site, so age control depended on an oxygen isotope stratigraphy from the shallower Site 883 [Keigwin, 1995], which was then transferred to Site 884 by detailed correlation of magnetic susceptibility records [Roberts *et al.*, 1997]. The oxygen isotope stratigraphy is not well defined in the vicinity of the MIS 7/6 boundary, so dating for this interval was achieved by interpolation. Roberts *et al.* [1997] argued that the excursion corresponds to the IBE on the basis of this age interpolation, which corresponds well with a large relative paleointensity minimum that correlates with a marked minimum at ~ 190 kyr in the global paleointensity stack of Guyodo and Valet [1999]. We show the VGP path for this excursion in Figure 9 and discuss it further below (details of the magnetic properties of ODP Site 884 are presented by Roberts *et al.* [1997]).

4. Discussion

[28] Although the sense of movement along the VGP paths is opposite for the IBE and the LE (i.e., counterclockwise versus clockwise), the striking similarity of the two sets of paths suggests that similar mechanisms must have prevailed in the Earth's core during the two excursions. In addition, the simple structure of the paths can be taken as a strong indication of a simple geometry of the transitional geomagnetic field for both excursions.

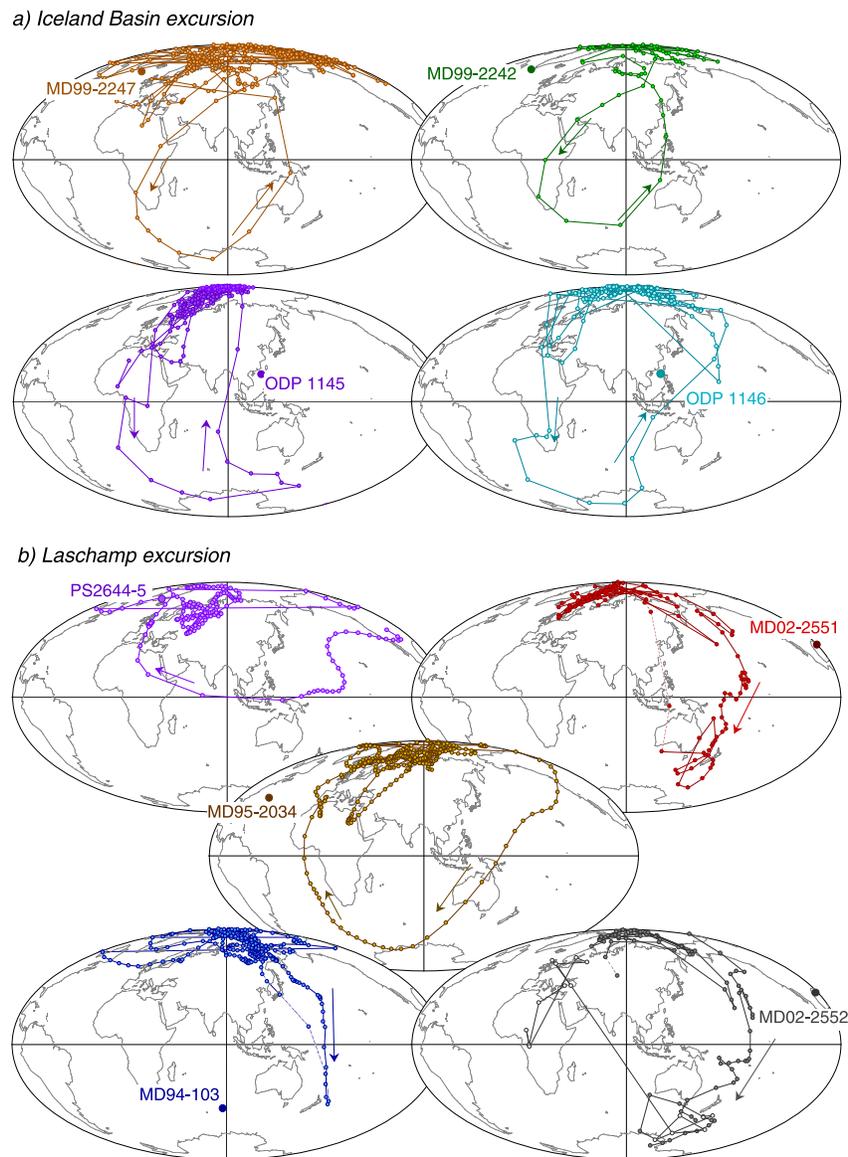


Figure 7. Paths of the virtual geomagnetic pole (VGP) during (a) the Iceland Basin excursion and (b) the Laschamp excursion for the different studied cores. Dashed lines indicate the poorly defined parts of the paths, and open symbols in core MD02-2552 are for the results obtained from discrete samples. The respective coring sites are illustrated by a dot with the same color as the VGPs, and the name of the core is reported nearby. The arrows indicate the sense of looping of the VGP paths.

Our data therefore do not support the generally held idea that the pronounced intensity minima that coincide with directional excursions reflect the emergence of nondipole geomagnetic components [e.g., Merrill and McFadden, 1994; Guyodo and Valet, 1999]. If nondipole fields were dominant, one should observe widely different paths at the different sites, which is not the case here. On the contrary, the VGP paths and the intensity records for the two excursions are consistent with a decrease of the axial dipole, a substantial transitional equatorial dipole and a significantly reduced non-

dipole field relative to the axial dipole. During the first, N→S part of the IBE path, over Europe and Africa, the g_1^1 term of the equatorial dipole appears to be preponderant, while h_1^1 appears to be dominant during the R→N part of the excursion. For the LE, the opposite is true, with the first part dominated by h_1^1 and the second part dominated by g_1^1 . As indicated by the relative paleointensity records, the intensity of the field is substantially reduced during the excursions. Therefore the dominance of dipolar fields during the excursions implies that the amplitudes of the nondipole components were also

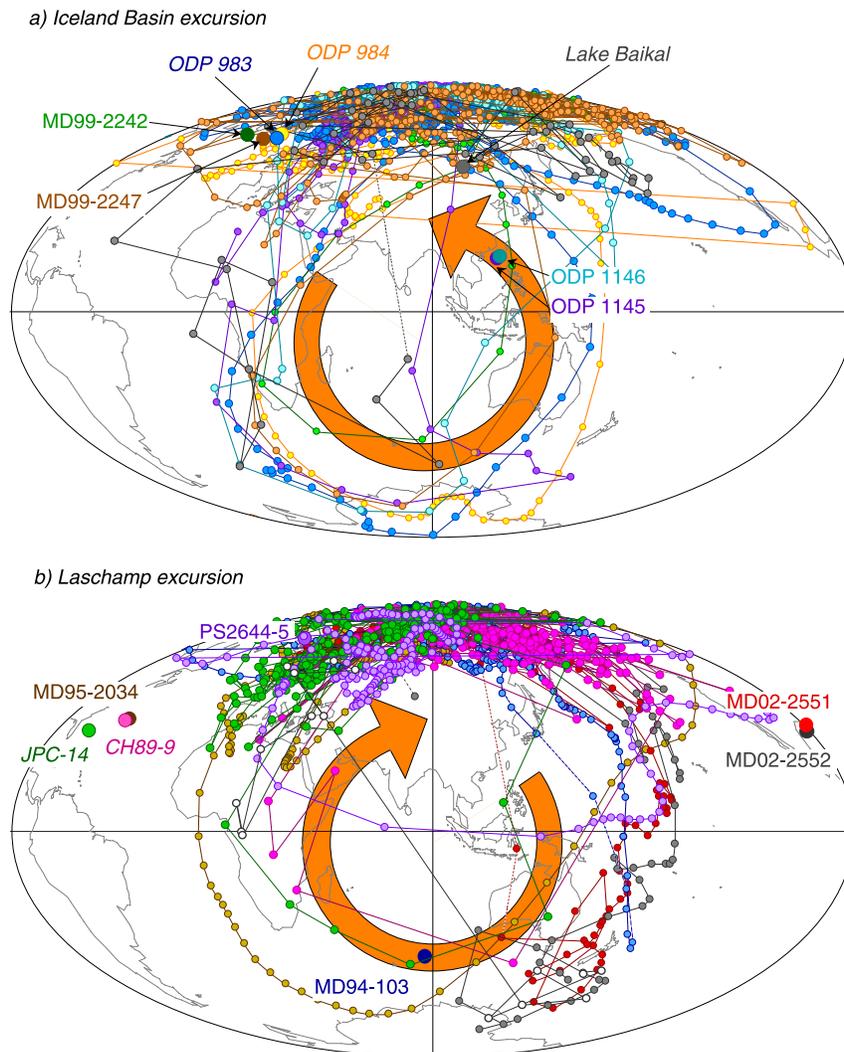


Figure 8. All of the VGP paths shown in Figure 7 are superimposed for (a) the Iceland Basin excursion and (b) the Laschamp excursion. Records reported in the literature are also shown. The large orange arrows illustrate the sense of looping, which is common to all records from each excursion. The loops are counterclockwise for the Iceland Basin excursion and clockwise for the Laschamp excursion.

substantially reduced during the excursions relative to both the axial dipole and to their usual nonexcursion values. While additional records from a wider geographical area (e.g., the Pacific hemisphere) need to be considered to fully assess the geometry of the excursions, the similarity of records with such broad geographical coverage makes it difficult to consider the excursions as being largely non-dipolar.

[29] The fact that our records, and other published records of the IBE and the LE, unambiguously support the hypothesis that the geomagnetic field during these excursions was characterized by a simple, dipole-dominated, geometry begs the ques-

tion as to whether this could generally be the case for all excursions. The fact that we have only studied two excursions in detail, and that only a small number of detailed studies have been published, makes this question impossible to answer. Nevertheless, it should be noted that the VGP paths for the excursion recorded at Summer Lake, Long Valley and Pringle Falls [Liddicoat, 1990; Herrero-Bervera *et al.*, 1994; Negrini *et al.*, 1994], which all represent the same excursion (the Pringle Falls excursion), contain clockwise loops like the Laschamp excursion. However, these loops lie on different longitudes to those presented here. This indicates that at least some excursions follow different VGP paths. Regardless, the nature of the configuration of the excursions for the Prin-

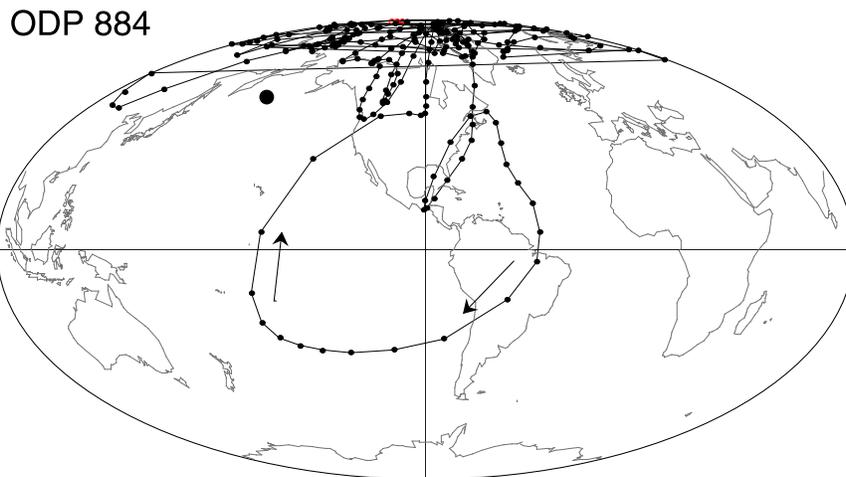


Figure 9. VGP path for the excursion reported by *Roberts et al.* [1997] in the vicinity of the MIS 7/6 boundary. The VGP path is completely different than those shown for all known records of the IBE (Figure 8a), but it is similar to records of the poorly dated Pringle Falls excursion from lacustrine sediments from western North America [*Liddicoat, 1990; Herrero-Bervera et al., 1994; Negrini et al., 1994*]. Given the indirect nature of the dating evidence associated with the excursion at ODP Site 884, we cannot confidently link it to the IBE, so we do not include it in our synthesis in Figure 8.

gle Falls excursion cannot be more firmly established without a broader geographic distribution of detailed records. The VGP path shown in Figure 9 for the excursion reported by *Roberts et al.* [1997] follows a clockwise loop and a geographical pattern that is more similar to the Pringle Falls paths [*Liddicoat, 1990; Herrero-Bervera et al., 1994; Negrini et al., 1994*] than to the counterclockwise pattern described above for the unambiguously identified IBE records presented here. Given that this excursion record is dated on the basis of an indirect correlation, we cannot consider its dating with the same degree of confidence as the other IBE records presented here. Should more direct evidence unambiguously tie the stratigraphic interval associated with this excursion at ODP Site 884 to the MIS 7/6 transition, and therefore identify this excursion as a record of the IBE, then its associated VGP path (Figure 9) would be an outlier with respect to all of the other records reported here. A slightly different, more complicated geometry should then be assumed for the IBE. However, restricting our synthesis to records with the most precise chronologies suggests a simple geometry for the geomagnetic field during the IBE.

[30] The east Asian longitudinal band identified in the excursions VGP paths coincides with one of the preferred longitudinal bands for geomagnetic reversal paths suggested by *Laj et al.* [1991]. Our data provide new evidence that this longitudinal band might play an important role during geomag-

netic reversals, whether it be associated with reversals or excursions. The longitudinal band over western Europe and Africa, on the other hand, is not evident in compilations of sedimentary reversal paths [*Laj et al., 1991*]. However, it does appear in more recent sedimentary records compiled and discussed by *Glen et al.* [1994, 1999]. Some of the Western American records, however, may have been distorted by factors associated sedimentary recording of the paleomagnetic field [see, e.g., *Quidelleur et al., 1995*]. Recently published volcanic records of geomagnetic reversals reported by *Valet and Herrero-Bervera* [2003] also document transitional VGPs over Africa and Europe. These authors identified three “preferred longitudinal bands”: the two already suggested from sedimentary data and the same western European-African band evident here.

[31] Considering the suggestion by *Gubbins* [1999] that the geomagnetic field might reverse in the Earth’s liquid outer core during excursions, which occurs on timescales of 500 years or so, but not, as must be the case for polarity reversals, in the solid inner core, where the field changes by diffusion with timescales of 3 kyr, we have estimated the duration of the IBE in the studied cores using the SPECMAP-tuned oxygen isotope stratigraphy for the respective cores. For all four records, the results indicate a duration of 2,000 years or less for the full directional excursion (N→R→N) associated with the IBE. This is consistent with the 1500–2000

year duration of the LE based on the NAPIS-75 [Laj *et al.*, 2000] and GLOPIS-75 records [Laj *et al.*, 2004]. This provides clear support for the suggestion of Gubbins [1999] that there is a distinction between geomagnetic reversals and excursions. On the other hand, the observed coincidence between the two longitudinal bands for transitional VGPs during the IBE and LE and those for some sedimentary and volcanic records of reversals also indicates an inherent link in the mechanisms of the geodynamo that led to a reversal or an excursion.

5. Conclusions

[32] The paleomagnetic records presented in this study strongly suggest that the geomagnetic field during the IBE and the LE was characterized by a simple transitional geometry. The axial dipole underwent a substantial decrease, while the equatorial dipole was preponderant during the excursions. Contrary to usually held ideas, the full nondipole field also decreased significantly relative to the axial dipole field, although the presence of a limited nondipole contribution cannot be excluded. This last possibility could account for the second-order differences among the paths, along with possible (unrecognized) core deformation or artifacts produced by sampling and measurement techniques.

[33] The VGPs for the two excursions (separated in time by 140 kyr) followed the same path, which might suggest a deep-Earth (i.e., lower mantle) control on the excursions field geometry that is stable for longer time periods than the time constants associated with the outer core. Nevertheless, despite the fact that the excursions VGPs follow the same path, the sense of looping of the paths is opposite for the Iceland Basin and Laschamp excursions. The duration of these excursions, based on constraints from oxygen isotope stratigraphy, is estimated at less than 2,000 years. This duration is shorter than the ~ 3 kyr timescale of diffusive field changes in the Earth's solid inner core, which must reverse polarity in order for a full geomagnetic reversal to occur. The fact that our estimate of excursion duration is shorter than 3 kyr provides support for the suggestion by Gubbins [1999] that there is a distinction between geomagnetic reversals and excursions. Nevertheless, the similarity of our excursions VGP paths with the longitudinal bands often observed in records of geomagnetic polarity transitions [Laj *et al.*, 1991; Valet and Herrero-Bervera, 2003] suggests that there could

also be an inherent link in the mechanisms that give rise to geomagnetic excursions and reversals.

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References

- Adkins, J. F., E. A. Boyle, L. Keigwin, and E. Cortijo (1997), Variability of the North Atlantic thermohaline circulation during the last interglacial, *Nature*, *390*, 154–156.
- Banerjee, S. K., J. W. King, and J. Marvin (1981), A rapid method for magnetic granulometry with applications to environmental studies, *Geophys. Res. Lett.*, *8*, 333–336.
- Baumgartner, S., J. Beer, M. Suter, B. Ditttrich-Hannen, H.-A. Synal, P. W. Kubik, C. Hammer, and S. Johnsen (1997), ^{36}Cl fallout in the Summit Greenland Ice Core Project ice core, *J. Geophys. Res.*, *102*, 26,659–26,662.
- Bassinot, F., L. Labeyrie, E. Vincent, X. Quidelleur, N. Shackleton, and Y. Lancelot (1994), The astronomical theory of climate and the age of the Brunhes-Matuyama magnetic reversal, *Earth Planet. Sci. Lett.*, *126*, 91–108.
- Brachfeld, S., C. Kissel, C. Laj, and A. Mazaud (2004), Behavior of U-channels during acquisition and demagnetization of remanence: Implications for paleomagnetic and rock-magnetic measurements, *Phys. Earth Planet. Inter.*, *145*, 1–8.
- Channell, J. E. T. (1999), Geomagnetic paleointensity and directional secular variation at Ocean Drilling Program (ODP) Site 984 (Bjorn Drift) since 500 ka: Comparisons with ODP Site 983 (Gardar Drift), *J. Geophys. Res.*, *104*, 22,937–22,951.
- Channell, J. E. T., D. A. Hodell, and B. Lehman (1997), Relative geomagnetic paleointensity and $\delta^{18}\text{O}$ at ODP Site 983/Gardar Drift, North Atlantic since 350 ka, *Earth Planet. Sci. Lett.*, *153*, 103–118.
- Clemens, S. C., and W. L. Prell (2003), Data report: Oxygen and carbon isotopes from Site 1146, Northern South China Sea, *Proc. Ocean Drill. Program Sci. Results* [online], *184*, 1–8.
- Clement, B. (1991), Geographical distribution of transitional VGPs: Evidence for non-zonal equatorial symmetry during the Matuyama-Brunhes geomagnetic reversal, *Earth Planet. Sci. Lett.*, *104*, 48–58.

- Dansgaard, W., et al. (1993), Evidence for general instability of past climate from a 250-kyr-ice-core record, *Nature*, *364*, 218–220.
- Day, R., M. Fuller, and V. A. Schmidt (1977), Hysteresis properties of titanomagnetite: Grain-size and compositional dependence, *Phys. Earth Planet. Inter.*, *13*, 260–267.
- Glen, J., R. S. Coe, and J. C. Liddicoat (1994), Persistent features of polarity transition records from western North America, *Geophys. Res. Lett.*, *21*, 1165–1168.
- Glen, J., R. S. Coe, and J. C. Liddicoat (1999), A detailed record of paleomagnetic field change from Searles Lake, California: 2. The Gauss/Matuyama polarity reversals, *J. Geophys. Res.*, *104*, 12,883–12,894.
- Gubbins, D. (1999), The distinction between geomagnetic excursions and reversals, *Geophys. J. Int.*, *137*, F1–F3.
- Guillou, H., B. S. Singer, C. Laj, C. Kissel, S. Scaillet, and B. R. Jicha (2004), On the age of the Laschamp geomagnetic excursion, *Earth Planet. Sci. Lett.*, *227*, 331–341.
- Guyodo, Y., and J.-P. Valet (1999), Global changes in intensity of the Earth's magnetic field during the past 800 kyr, *Nature*, *399*, 249–252.
- Herrero-Bervera, E., C. E. Helsley, A. M. Sama-Wojcicki, K. R. Lajoie, C. E. Meyer, M. O. McWilliams, R. M. Negrini, B. D. Turrin, J. M. Donnelly-Nolan, and J. C. Liddicoat (1994), Age and correlation of a paleomagnetic episode in the western United States by ⁴⁰Ar/³⁹Ar dating and tephrochronology: The Jamaica, Blake or a new polarity episode?, *J. Geophys. Res.*, *99*, 24,091–24,103.
- Hill, H. W., B. P. Flower, D. J. Hollander, and T. M. Quinn (2004), Evidence for oceanic/continental climate linkages during freshwater inputs to the Gulf of Mexico, *Eos Trans. AGU*, *85*(47), Fall Meet. Suppl., Abstract PP44A-07.
- Keigwin, L. D. (1995), Oxygen isotope stratigraphy from Hole 883D, Leg 145, *Proc. Ocean Drill. Program Sci. Results*, *145*, 257–264.
- King, J. W., and J. E. T. Channell (1991), Sedimentary magnetism, environmental magnetism and magnetostratigraphy, *U.S. Natl. Rep. Int. Union Geod. Geophys. 1987–1990, Rev. Geophys.*, *29*, 358–370.
- Kissel, C., C. Laj, L. Labeyrie, T. Dokken, A. Voelker, and D. Blamart (1999), Rapid climatic variations during marine isotopic stage 3: Magnetic analysis of sediments from Nordic seas and North Atlantic, *Earth Planet. Sci. Lett.*, *171*, 489–502.
- Kissel, C., C. Laj, S. Clemens, and P. Solheid (2003), Magnetic signature of environmental changes in the last 1.2 My at ODP Site 1146, South China Sea, *Mar. Geol.*, *201*, 119–132.
- Laj, C., A. Mazaud, R. Weeks, M. Fuller, and E. Herrero-Bervera (1991), Geomagnetic reversal paths, *Nature*, *351*, 447.
- Laj, C., C. Kissel, A. Mazaud, J. E. T. Channell, and J. Beer (2000), North Atlantic palaeointensity stack since 75 ka (NAPIS-75) and the duration of the Laschamp event, *Philos. Trans. R. Soc. London, Ser. A*, *358*, 1009–1025.
- Laj, C., C. Kissel, and J. Beer (2004), High resolution global paleointensity stack since 75 kyr (GLOPIS-75) calibrated to absolute values, in *Timescales of the Paleomagnetic Field, Geophys. Monogr. Ser.*, vol. 145, edited by J. E. T. Channell et al., pp. 255–265, AGU, Washington, D. C.
- Langereis, C. G., A. Van Hoof, and P. Rochette (1992), Longitudinal confinement of geomagnetic reversal paths: Sedimentary artefact or true field behavior?, *Nature*, *358*, 226–229.
- Lehman, B., C. Laj, C. Kissel, A. Mazaud, M. Paterne, and L. Labeyrie (1996), Relative changes of the geomagnetic field intensity during the last 280 kyr from piston cores in the Açores area, *Phys. Earth Planet. Inter.*, *93*, 269–284.
- Liddicoat, J. C. (1990), Aborted reversal of the palaeomagnetic field in the Brunhes Normal Chron in east-central California, *Geophys. J. Int.*, *102*, 747–752.
- Lowrie, W. (1990), Identification of ferromagnetic minerals in a rock by coercivity and unblocking temperature properties, *Geophys. Res. Lett.*, *17*, 159–162.
- Lund, S. P., T. Williams, G. D. Acton, B. Clement, and M. Okada (2001), Brunhes Chron magnetic field excursions recovered from Leg 172 sediments, *Proc. Ocean Drill. Program Sci. Res.* [CD-ROM], *172*, 1–18.
- Lund, S. P., M. Schwartz, L. Keigwin, and T. Johnson (2005), Deep-sea sediment records of the Laschamp geomagnetic field excursion (<41,000 calendar years before present), *J. Geophys. Res.*, *110*, B04101, doi:10.1029/2003JB002943.
- Mazaud, A. (2005), User-friendly software for vector analysis of the magnetization of long sediment cores, *Geochem. Geophys. Geosyst.*, *6*, Q12006, doi:10.1029/2005GC001036.
- Mazaud, A., M. A. Sicre, U. Ezat, J. J. Pichon, J. Duprat, C. Laj, C. Kissel, L. Beaufort, E. Michel, and J. L. Turon (2002), Geomagnetic assisted stratigraphy and SST changes in core MD94–103 (southern Indian Ocean): Possible implications for North-South climatic relationships around H4, *Earth Planet. Sci. Lett.*, *201*, 159–170.
- McFadden, P., C. E. Barton, and R. T. Merrill (1993), Do virtual geomagnetic poles follow preferred paths during geomagnetic reversals?, *Nature*, *361*, 342–344.
- Merrill, R. T., and P. L. McFadden (1994), Geomagnetic stability: Reversal events and excursions, *Earth Planet. Sci. Lett.*, *121*, 57–69.
- Negrini, R. M., D. B. Erbes, A. P. Roberts, K. L. Verosub, A. M. Sama-Wojcicki, and C. E. Meyer (1994), Repeating waveform initiated by a 180–190 ka geomagnetic excursion in western North America: Implications for field behavior during polarity transitions and subsequent secular variation, *J. Geophys. Res.*, *99*, 24,105–24,119.
- Nowaczyk, N. R., and M. Antonow (1997), High-resolution magnetostratigraphy of four sediment cores from the Greenland Sea—I. Identification of the Mono Lake excursion, Laschamp, and Biwa I/Jamaica geomagnetic polarity events, *Geophys. J. Int.*, *131*, 310–324.
- Nowaczyk, N. R., and M. Baumann (1992), Combined high-resolution magnetostratigraphy and nannofossil biostratigraphy for the late Quaternary Arctic Ocean sediments, *Deep Sea Res., Part II*, *39*, 567–601.
- Oda, H., K. Nakamura, T. Ikehara, M. Nishimura, and O. Khlystov (2002), Paleomagnetic record from Academician Ridge, Lake Baikal: A reversal excursion at the base of marine oxygen isotope stage 6, *Earth Planet. Sci. Lett.*, *202*, 117–132.
- Quidelleur, X., and J.-P. Valet (1994), Paleomagnetic records of excursions and reversals: Possible biases caused by magnetization artefacts, *Phys. Earth Planet. Inter.*, *82*, 27–48.
- Quidelleur, X., J. Holt, and J. P. Valet (1995), Confounding influence of magnetic fabric on sedimentary records of a field reversal, *Nature*, *374*, 246–249.
- Roberts, A. P., and M. Winklhofer (2004), Why are geomagnetic excursions not always recorded in sediments? Constraints from post-depositional remanent magnetization lock-in modelling, *Earth Planet. Sci. Lett.*, *227*, 345–359.

- Roberts, A. P., B. Lehman, R. J. Weeks, K. L. Verosub, and C. Laj (1997), Relative paleointensity of the geomagnetic field over the last 200,000 years from ODP sites 883 and 884, North Pacific Ocean, *Earth Planet. Sci. Lett.*, *152*, 11–23.
- Sagnotti, L., P. Rochette, M. Jackson, F. Vadeboin, J. Dinarès-Turell, A. Winkler, and “Mag-Net” Science Team (2003), Inter-laboratory calibration of low field magnetic and anhysteretic susceptibility measurements, *Phys. Earth Planet. Inter.*, *138*, 25–38.
- Stoner, J. S., J. E. T. Channell, D. A. Hodell, and C. D. Charles (2003), A ~580 kyr paleomagnetic record from the sub-Antarctic South Atlantic (Ocean Drilling Program Site 1089), *J. Geophys. Res.*, *108*(B5), 2244, doi:10.1029/2001JB001390.
- Tauxe, L. (1993), Sedimentary records of relative paleointensity of the geomagnetic field: Theory and practice, *Rev. Geophys.*, *31*, 319–354.
- Valet, J.-P., and E. Herrero-Bervera (2003), Some characteristics of geomagnetic reversals inferred from detailed volcanic records, *C. R. Geosci.*, *335*, 79–90.
- Valet, J.-P., P. Tucholka, V. Courtillot, and L. Meynadier (1992), Palaeomagnetic constraints on the geometry of the geomagnetic field during reversals, *Nature*, *356*, 400–407.
- Wagner, G., J. Beer, C. Laj, C. Kissel, J. Mazarik, R. Muscheler, and H. A. Synal (2000), Chlorine-36 evidence for the Mono Lake event in the Summit GRIP ice core, *Earth Planet. Sci. Lett.*, *181*, 1–6.
- Weeks, R., C. Laj, L. Endignoux, M. Fuller, A. Roberts, R. Manganne, E. Blanchard, and W. Goree (1993), Improvements in long-core measurement techniques: Applications in palaeomagnetism and palaeoceanography, *Geophys. J. Int.*, *114*, 651–662.
- Weeks, R. J., C. Laj, L. Labeyrie, L. Endignoux, A. Mazaud, A. P. Roberts, C. Kissel, and E. Blanchard (1995), Rock magnetism and normalized NRM intensity during the last 240,000 years in central North Atlantic piston cores, *Phys. Earth Planet. Inter.*, *87*, 213–229.
- Yamazaki, T., and N. Ioka (1994), Long-term secular variation of the geomagnetic field during the last 200 kyr recorded in sediment cores from the western equatorial Pacific, *Earth Planet. Sci. Lett.*, *128*, 527–544.