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A summary of Brunhes paleomagnetic field variability recorded in Ocean Drilling Program cores

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Abstract

The Ocean Drilling Program (ODP) has recovered many long sediment sequences from around the World that contain medium to high-resolution paleomagnetic records of Brunhes age. These records have provided an important new global view of geomagnetic field variability during 'stable' magnetic (dipole) polarity that could not be recovered by conventional terrestrial or deep-sea piston coring. The ODP paleomagnetic records of directional variability can be routinely recovered and used regionally as a very high-resolution relative chronostratigraphic tool (±200 yr resolution). ODP paleomagnetic records of Brunhes age relative paleointensity have dramatically improved our understanding of global geomagnetic field intensity. These records document the global-scale pattern of paleointensity and demonstrate its use as a high-resolution relative chronostratigraphic tool that under ideal conditions could have a precision of ±500 yr**.** ODP paleomagnetic records and associated oxygen isotope chronostratigraphies have also greatly improved our understanding of the number and ages of Brunhes geomagnetic field excursions, and their relationship to normal directional secular variation and paleointensity variability. Although significant progress has been made though ODP paleomagnetic studies of Brunhes-aged sediments, it is clear that more work is needed to further resolve and define the detailed global pattern of Brunhes PSV and its relationship to excursions and true polarity reversals.

Keywords: Ocean Drilling Program (ODP); Paleomagnetism; Paleomagnetic secular variation; Paleointensity; Excursions

1. Introduction

The source of the Earth's magnetic field has been the subject of scientific study for more than 400 years (e.g., Gilbert, 1600). Most of the field measured at the Earth's surface is of internal origin, generated by hydromagnetic dynamo action in the liquid-iron outer core (for overview, see Merrill et al., 1998). Historic measurements of the geomagnetic field have documented its primarily dipolar spatial structure at the Earth's surface and its short-term temporal variability, which is termed secular variation. One notable characteristic of the Earth's magnetic field and secular variation is its full vector nature, with significant space/time variability in both directions and intensity. Recent historic secular variation (HSV) studies (e.g., Thompson and Barraclough, 1982; Bloxham and Gubbins, 1985; Olson et al., 2002) have characterized the global pattern of short-term secular variation and have related its variability to the core dynamo process.

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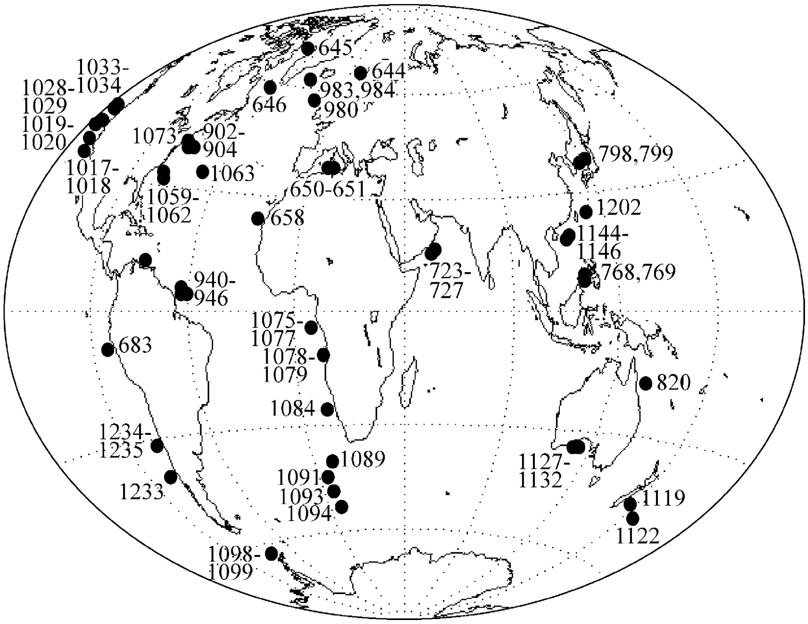

Fig. 1. Selected ODP drilling sites that have at least 10 cm/kyr sedimentation rates during the Brunhes chron (0–780,000 yr. BP) and contain at least some moderate to high-resolution paleomagnetic evidence for PSV, relative paleointensity, or paleomagnetic excursions.

Paleomagnetic studies make it clear, however, that the Earth's magnetic field has undergone a much wider range of spatial and temporal variations than has been seen in historic times. Geomagnetic field polarity reversals have occurred intermittently in time (e.g., Cande and Kent, 1995), and the intervening time intervals of stable (dipole) polarity contain prehistoric paleomagnetic secular variation (PSV) larger in amplitude and broader in frequency content than HSV. PSV studies have also documented occasional excursions (e.g., Watkins, 1976; Verosub and Banerjee, 1977), which are anomalous PSV fluctuations that may be aborted polarity reversals (e.g., Opdyke, 1972) or represent a fundamentally different non-dipolar state of the geomagnetic field (e.g., Lund et al., 1998, 2001a,b).

Our most complete understanding of PSV has come from the paleomagnetic study of sediment sequences, which ideally permit precise dating of the sequence and the development of good sequential records of both paleomagnetic directional and intensity variability. Fine-grained sediment sequences can accurately record the local magnetic field variability at depositional sites with moderate (>10 cm/kyr) to high resolution (>20 cm/kyr) and with some degree of smoothing depending on sediment accumulation rates and bioturbation. The Ocean Drilling Program (which succeeded the Deep Sea Drilling Project) began in 1983 and has conducted 110 Legs (Legs 100–210) comprised of 653 individual coring Sites (Sites 653–1277) over the last twenty years. During that time, at least 69 sites (Fig. 1) from all over the World have been drilled into deep-sea sediments that have at least moderate (>10 cm/kyr) resolution records of paleomagnetic field variability. The ODP has routinely recovered pristine sequences of deep-sea sediments hundreds of meters in length from each site using the Advanced Piston Corer (APC). The recovered sediment sequences are significantly longer than could be recovered with any other coring method. The geomagnetic field behavior estimated from paleomagnetic studies of these sites has significantly improved our understanding of PSV and its relationship to paleointensity, excursions and polarity reversals. Below we summarize some key geomagnetic observations of the Earth's magnetic field during the Brunhes epoch (last 780,000 years) that have been obtained from ODP cores.

2. Brunhes paleomagnetic secular variation

Many paleomagnetic records of directional secular variation have been recovered from sediments following the pioneering efforts of McNish and Johnson (1938), Johnson et al. (1948), Nagata et al. (1949), and Mackereth (1971). However, most of these records are from terrestrial lake sequences in the northern hemisphere that only sample field variability for the last 20,000 years or so. The ODP has offered an unparalleled opportunity to sample continuous sediment sequences that are much longer in duration and recover directional

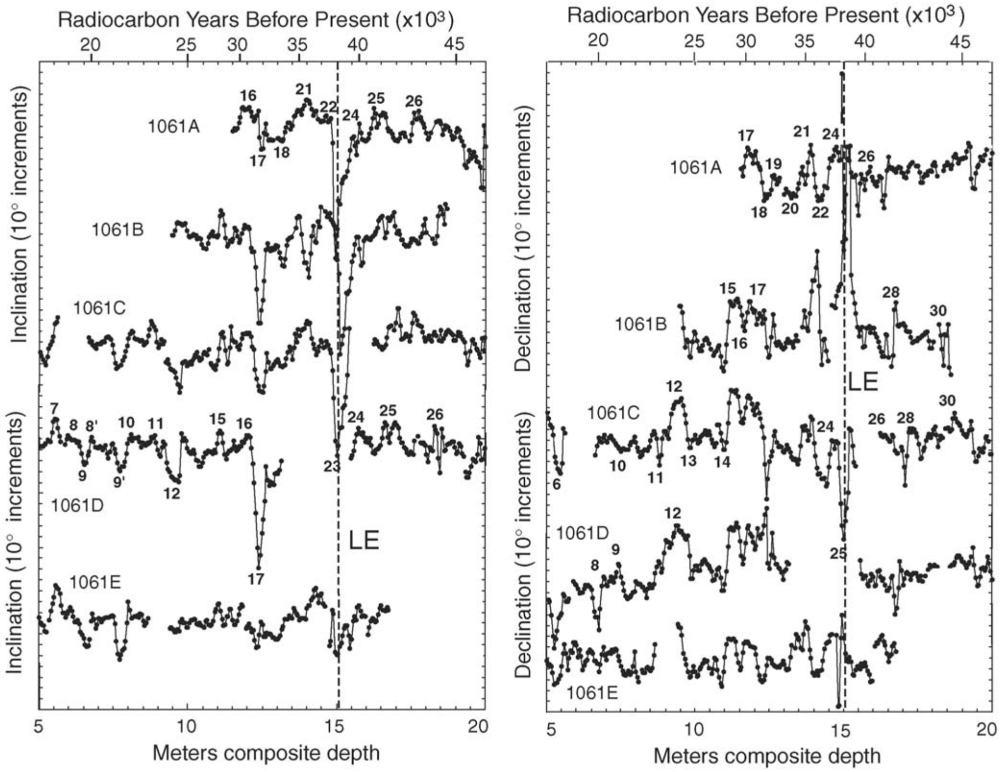

Fig. 2. PSV records from replicate Holes at ODP Site 1061 from the Blake/Bahama Outer Ridge, northwest Atlantic Ocean. Numbers indicate selected PSV features that are correlatable between holes and with paleomagnetic results from ODP Site1063 (Bermuda Rise), more than1000 km away (Fig. 3). LE indicates the location of the Laschamp excursion in these records. All records are shipboard measurements of archive core halves after 20 mT a.f. demagnetization (Lund et al., 2001b).

PSV records that come from many different parts of the Earth.

Most of the sites shown in Fig. 1 contain some moderate to high-resolution evidence for PSV during at least selected intervals of the Brunhes epoch (0-780,000 yr. BP). Legs 162, 169, 172, 177, and 202 were particularly successful in recovering long PSV records that were sometimes correlatable between sites more than 1000 km apart. For example, Figs. 2 and 3 indicate PSV records from ODP Sites 1061 (Blake/Bahama Outer Ridge) and 1063 (Bermuda Rise) for the interval 15,000 to 50,000 yr. BP. These PSV records both show that reproducible directional PSV records can be recovered from replicate holes at individual sites. The PSV records at these two sites, which are situated more than 1000 km apart, are also correlatable between them (see numbered features in Figs. 2 and 3) and with other PSV records from the same region (Lund et al., 2001a,b). Such reproducibility between holes at each site and between sites more than 1000 km apart validates the quality of the paleomagnetic records and indicates that PSV can be an excellent regional correlation tool with ∼±200 yr resolution (Lund, 1996).

Fig. 4 identifies another set of correlatable directional PSV records from Sites 1233 and 1234 (Chilean Margin) in the southern hemisphere. These records span generally the same interval as Figs. 2 and 3 and the numbered directional features indicate that, here too, PSV can be correlated between sites more than 500 km apart.

Finally, Fig. 5 shows the directional record for the entire Brunhes epoch from ODP Site 1062 (Blake/Bahama Outer Ridge) in the western North Atlantic Ocean. This record shows that distinctive directional variations occur over a wide range of timescales that extend from 10^2 to 10^5 years. Continuing analysis and correlations of such records are producing an unprecedented long-term understanding of directional PSV during the entire Brunhes chron.

Another feature of the directional PSV records in Figs. 2–5 is that they also contain evidence for the existence and temporal behavior of magnetic field excursions (see below). Such long directional PSV records are

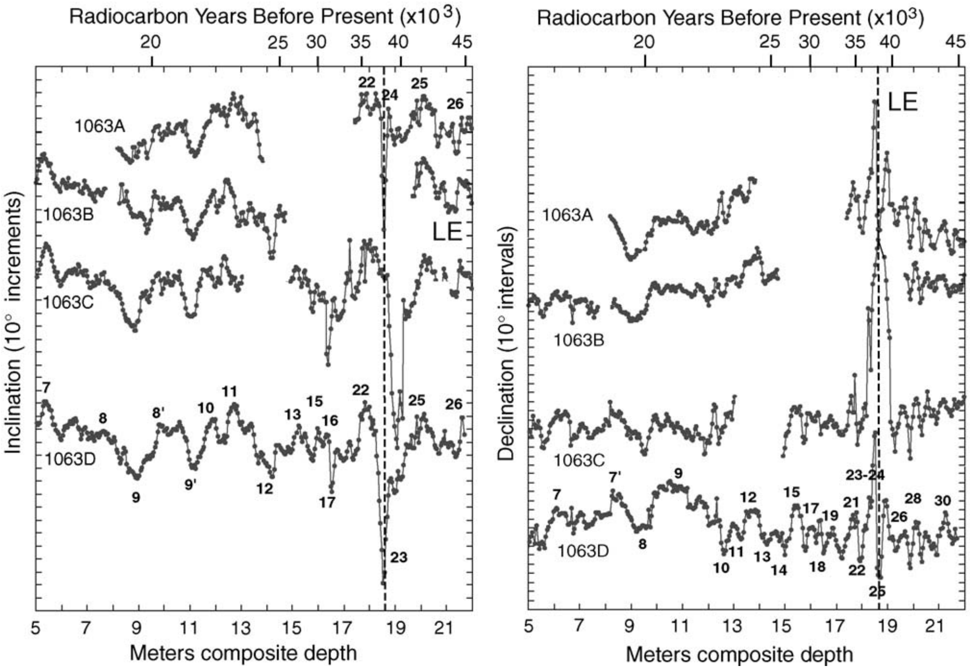

Fig. 3. PSV records from replicate Holes at ODP Site 1063 from the Bermuda Rise, northwest Atlantic Ocean. Numbers indicate selected PSV features that are correlatable between holes and with paleomagnetic results from ODP Site1061 (Blake/Bahama Outer Ridge), more than1000 km away (Fig. 2). LE indicates the location of the Laschamp Excursion in these records. All records are shipboard measurements of archive core halves after 20 mT a.f. demagnetization (Lund et al., 2001b).

almost our sole evidence for the dynamical relationship between 'normal' PSV and excursions.

3. Brunhes relative paleointensity

Another aspect of PSV studies, reconstructing the paleointensity variability of the geomagnetic field, has expanded greatly over the last 30 years or so with the development of relative paleointensity estimates from sediment sequences (e.g., Levi and Banerjee, 1976; King et al., 1983; Tauxe, 1993). Sediment relative paleointensity records have the advantage over volcanic paleointensity records in that relatively continuous and well-dated records can be obtained. However, they have one disadvantage in that they cannot uniquely determine the exact value of local field intensity, only its relative variation over time. Sediment relative paleointensity studies also suffer from the limitations related to sediment conditions (magnetic grain size, overall sediment composition, etc.) and how those change with time.

Sediment relative paleointensity studies in lakes have greatly improved our understanding of Holocene paleointensity (0–12,000 yr. BP) from around the World (e.g., King et al., 1983; Constable and McElhinny, 1985; Peck et al., 1996), but varying lake conditions have not permitted long-duration pre-Holocene records to be recovered routinely. Deep-sea sediment sequences have three inherent advantages over lake sediment sequences for relative paleointensity studies. First, many deep-sea sediment sequences have relatively little environmental variability for very long intervals of time permitting long, continuous relative paleointensity estimates from individual sites. Second, deep-sea sediment sequences are routinely associated with marine oxygen isotope records that provide first-order chronologies for the paleointensity records. Third, deep-sea sediment records can be recovered from many different parts of the world, as noted in Fig. 1, permitting a true global perspective on paleointensity variability.

A large number of medium-resolution relative paleointensity records for all or portions of the Brunhes chron have been recovered from ODP sites around the World (e.g., Tric et al., 1991; Valet and Meynadier, 1993). These records have established that paleointensity variability is correlatable on a global scale and therefore largely due to the main (dipole) portion of the field. Such studies have developed relative paleointensity as a chronostratigraphic tool complementary to marine oxygen isotope studies (Guyodo and Valet, 1996, 1999).

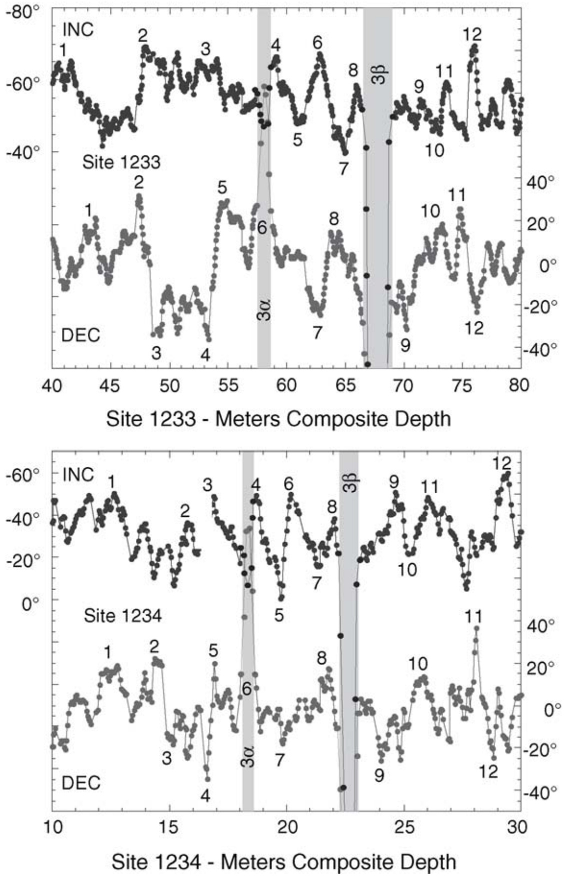

Fig. 4. Correlation of PSV records from ODP Sites 1233 (top) and 1234 (bottom), collected about 500 km apart from the southwest margin of Chile in the southeast Pacific Ocean. Selected correlatable PSV features are numbered for clarity. The grey intervals locate two excursions, 3α and 3β, that occur at both sites (Lund et al., 2006). These two excursions are equivalent in age (Lamy et al., 2004) to the Mono Lake and Laschamp Excursions, respectively. All records are shipboard measurements of archive core halves after 20 mT a.f. demagnetization. The Site 1233 record of Excursion 3β is shown at an expanded scale in Fig. 9.

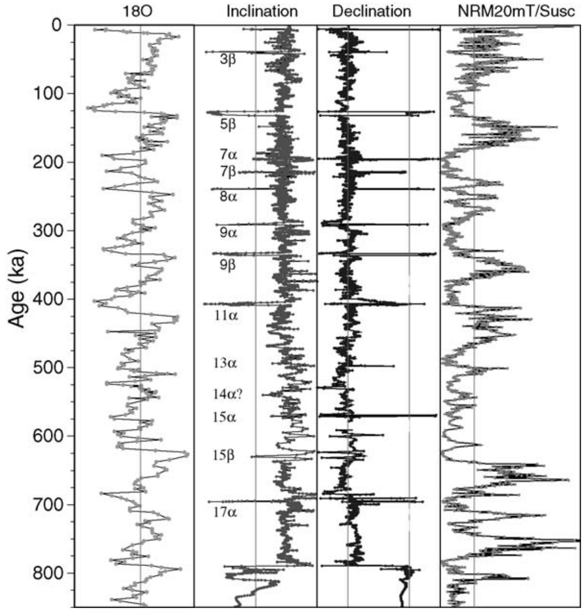

Fig. 5. ODP Site 1062 inclination, declination, and relative paleointensity records for the Brunhes chron. Thirteen magnetic field excursions, labeled 3β-13α, can be identified by anomalously low inclinations and southerly pointing declinations. These are all associated with intervals of low relative paleointensity. All records are shipboard measurements of archive core halves after 20 mT a.f. demagnetization. The relative paleointensity estimate is based on the ratio of NRM (after 20 mT a.f. demagnetization) divided by magnetic susceptibility. The age model was determined by Grützner et al. (2002) using the carbonate stratigraphy at Site 1062 and the oxygen isotope stratigraphy of Bassinot et al. (1994).

More recent paleomagnetic studies of higher-sediment accumulation rate ODP sites have further documented the pattern of paleointensity and its detailed correlation on a global scale. The highest resolution complete Brunhes chron relative paleointensity records have been recovered from ODP Sites 983 and 984 in the North Atlantic Ocean (Channell et al., 1997, 2004; Channell, 1999). These records are shown in Fig. 6 on their independent oxygen isotope age models. The replicate paleointensity records from two ODP sites situated more than 100 km apart are very similar and display a rich pattern of field variability at millennial and longer timescales. A recent paleointensity record from ODP Site 1089 in the South Atlantic Ocean (Stoner et al., 2003), shown in Fig. 7, can be compared with that from ODP Site 983, illustrating the strong overall similarity of paleointensity variability from different hemispheres, even on millennial timescales. Taken together, the ODP relative paleointensity records suggest that these records can be used as a high-resolution, relative chronostratigraphic tool with potentially millennial-scale resolution that is complementary to high-resolution oxygen-isotope chronostratigraphies.

4. Brunhes paleomagnetic field excursions

ODP paleomagnetic studies have also been instrumental in evaluating the existence, number, and pattern of field behavior for magnetic field excursions. A paleomagnetic excursion can be usefully defined as a short-duration (few thousand year) directional anomaly outside the “normal” range of secular variation. Excursions may denote imperfect records of short-duration polarity subchrons, although this has not been generally established, or they may reflect simply anomalous amplitude PSV (Lund et al., 2005).

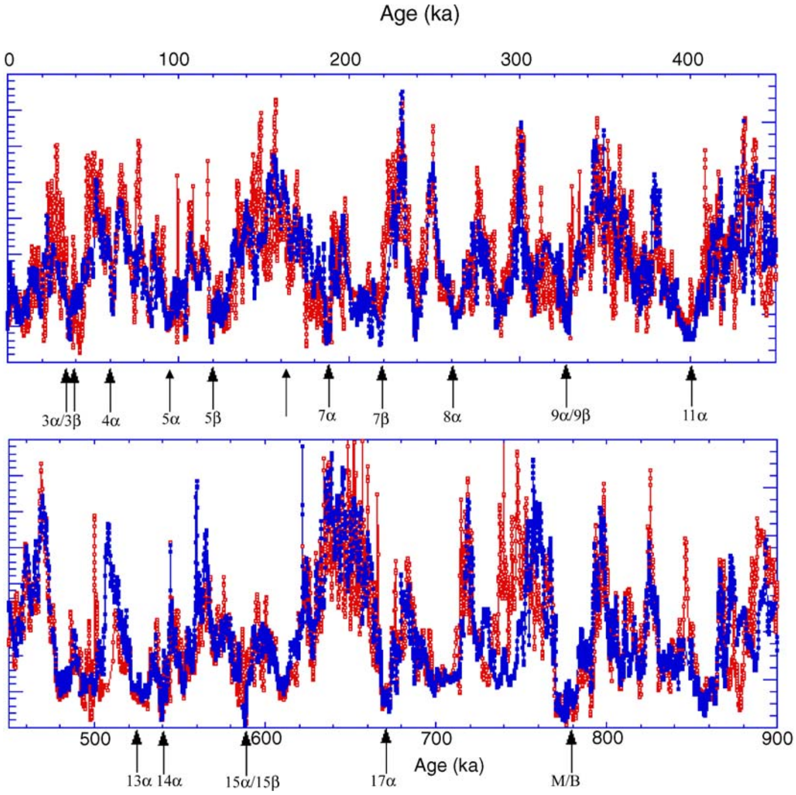

Fig. 6. Brunhes paleointensity record from ODP Sites 983/984 (Channell, 1999; Channell et al., 2004). Age models are independent and based on oxygen isotope data. Note the strong correspondence in the relative paleointensity estimates from two sites about 100 km apart. These records represent our most high-resolution evidence for overall Brunhes chron paleointensity variability. The ages of known Brunhes chron excursions (Table 1) are indicated by arrows. Note that all excursions occur in distinctive intervals of low paleointensity.

Apart from the Reunion Subchron, all chrons in the Cande and Kent (1992, 1995) polarity timescale for the last 80 Myr (CK92/95) have duration >30 kyr. "Cryptochrons" (duration <30 kyr) observed in oceanic magnetic anomaly records and listed in CK92/95 could be caused either by brief polarity subchrons or paleointensity lows, or both. In the Brunhes and Matuyama chrons of CK92/95, only two "cryptochrons" are recognized in marine magnetic anomaly data, with estimated ages of 500 ka and 1.2 Ma (Cobb Mt. Subchron). It is appears that excursions/subchrons are generally too brief to be recorded in basaltic basement at normal rates of seafloor spreading.

Ten years ago, the majority of paleomagnetists would have advocated the existence of about five geomagnetic excursions within the Brunhes chron. The five excursions on most lists, would have been: (1) The Mono Lake Event at about 30 ka (Liddicoat and Coe, 1979), (2) The Laschamp Event at about 40 ka (Bonhommet and Babkine, 1967; Bonhommet and Zahringer, 1969; Levi et al., 1990), (3) The Blake Event at about 120 ka (Smith and Foster, 1969; Tric et al., 1991; Zhu et al., 1994), (4) The Pringle Falls Event at about 220 ka (Herrero-Brevera et al., 1989) and (5) The Big Lost Event at ∼565 ka (Negrini et al., 1987; Champion et al., 1988).

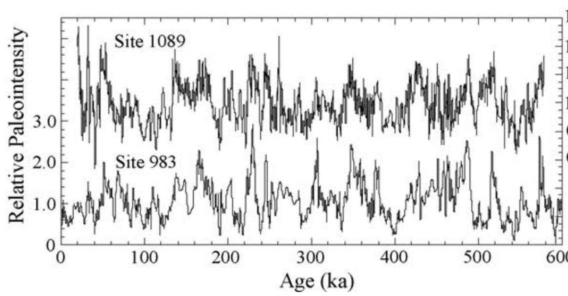

Fig. 7. Brunhes chron relative paleointensity record from southern hemisphere ODP Site 1089 (Stoner et al., 2003) compared with the record from ODP Site 983 (Channell, 1999) in the North Atlantic Ocean (Fig. 6). Age for Site 983 relative paleointensity in this figure is derived through optimal correlation of benthic oxygen isotopes and paleointensity to those at Site 1089 (after Fig. 17, Stoner et al., 2003).

Table 1
Summary of paleomagnetic evidence for existence/age of Brunhes chron excursions[a]

Excursion[b]	Stage[c]	Estimated age (ka)	Selected localities[d]	Principal refs.[e]
Mono Lake/3α	3	33 ± 1	Mono Lake, Arctic/202	1
Laschamp/3β	3	41 ± 1	Europe/Arctic/172/202	2
Norweg.-Greenland Sea/4α	4	61 ± 2	Arctic/202	3
Fram Strait I/5α	*5.2/5.3*	*~100*	*Arctic*	*4*
Blake/5β	5.5	123 ± 3	N. Atlantic/Arctic/172	5
Baffin Bay/Fram Strait II/6α	*6.2/6.3*	*~160*	*Arctic*	6
Iceland Basin/7α	6.6/7.1	~190	N. Atlantic/Arctic/Baikal/162/172	7
Pringle Falls/Summer Lake II	7.5	~220	W. USA/Arctic/172	8
CR0/8α	*8*	*~260*	*Mediterranean/Arctic/172*	*9*
9α	*8/9*	*~290–310*	*Arctic/172*	*10*
CR1/9β	*9*	*~330*	*Mediterranean/Arctic/172*	*11*
11α	*11*	*~400*	*Arctic/172*	*12*
CR2/13α	*13*	*480–510*	*W. USA/Arctic/172*	*13*
14α	*14*	*~535*	*162/172*	*14*
Big Lost/CR3	15	~575	W. USA/Mediterranean/162/172	15
La Palma/15β	15	~605	N. Atlantic/162/172	16
17α	*17*	*~665*	*Japan/162/172*	*17*

[a] Notes: italics indicate more poorly documented excursions.
[b] Most commonly cited name (or names).
[c] SPECMAP stage assignments summarized in Martinson et al. (1987).
[d] Selected localities where excursion records are known, numbers indicate ODP Legs.
[e] Principal references with good quality paleomagnetic and chronostratigraphic evidence for excursions: 1 – Liddicoat and Coe (1979), Nowaczyk and Antonow (1997), Nowaczyk and Knies (2000); 2 – Bonhommet and Babkine (1967), Bonhommet and Zahringer (1969), Levi et al. (1990), Kissel et al. (1999), Lund et al. (2001a), Lund et al. (in press); 3 - Bleil and Gard (1989), Nowaczyk et al. (1994), Nowaczyk and Frederichs (1999); 4 – Nowaczyk and Baumann (1992), Nowaczyk and Fredericks (1999); 5 – Smith and Foster (1969), Tric et al. (1991), Lund et al. (in review); 6 – Aksu (1983), Nowaczyk and Baumann (1992), Nowaczyk and Fredericks (1999); 7 – Nowaczyk and Baumann (1992), Channell et al. (1997), Nowaczyk and Frederiks (1999), Channell (1999), Lund et al. (1998, 2001b), Oda et al. (2002), Stoner et al. (2003); 8 – Herrero-Bervera et al. (1994), Liddicoat (1990), Nowaczyk and Baumann (1992), Negrini et al. (1994), Nowaczyk and Fredericks (1999), Lund et al. (1998, 2001b), McWilliams (2001); 9 – Langereis et al. (1997), Lund et al. (1998, 2001b); 10 – Lund et al. (1998, 2001b); 11 – Bleil and Gard (1989), Langereis et al. (1997), Lund et al. (1998, 2001b), Stoner et al. (2003); 12 – Lund et al. (1998, 2001b); 13 - Langereis et al. (1997), Lund et al. (1998, 2001b); 14 – Lund et al. (1998, 2001b), Channell et al. (2004); 15 – Champion et al. (1988), Langereis et al. (1997), Lund et al. (1998, 2001b), Channell et al. (2004); 16 - Quidelleur et al. (1999), Lund et al. (1998, 2001b), Channell et al. (2004); 17 - Lund et al. (1998, 2001b), Biswas et al. (1999), Channell et al. (2004).

Following Champion et al. (1988) in which the authors made the case for eight excursions within the Brunhes chron, the number of excursions in the Brunhes chron has proliferated to 12–17 (Langereis et al., 1997; Lund et al., 1998, 2001a,b). With the advent of the Advanced Piston Corer (APC) that allows long sediment sequences to be acquired in pristine condition, ODP cores can now extend the search for excursions at a global scale over the entire Brunhes chron (e.g., Fig. 5). The presence of detailed oxygen-isotope records has also been instrumental in improving the age estimates for excursion records in deep-sea sediments. We have summarized the current understanding of the number and ages of Brunhes chron excursions in Table 1. All of these excursions appear to have been recorded in one or more ODP sites (labeled in Table 1). The preferred ages and names of the excursions are determined by what we consider to be the best available data. The key references are noted in Table 1. Some older papers that appear to document excursions (e.g., Wollin et al., 1971; Ryan, 1972; Kawai et al., 1972; Creer et al., 1980) are viewed with some skepticism due to the myriad of non-geomagnetic explanations that can account for excursional directions in sediments, and because of poor age control.

Valet and Meynadier (1993) pointed out that lows in relative paleointensity during the Brunhes chron from equatorial Pacific (ODP Leg 138) sediments appear synchronized with directional excursions detected elsewhere. The sedimentation rates in Leg 138 sediments are, however, too low to record geomagnetic excursions and therefore a direct correlation of excursions and paleointensity was not possible in these cores. The direct correlation of geomagnetic excursions to lows in paleointensity has since been achieved for the Laschamp Event (Laj et al., 2000), the Iceland Basin Event (Channell et al., 1997;

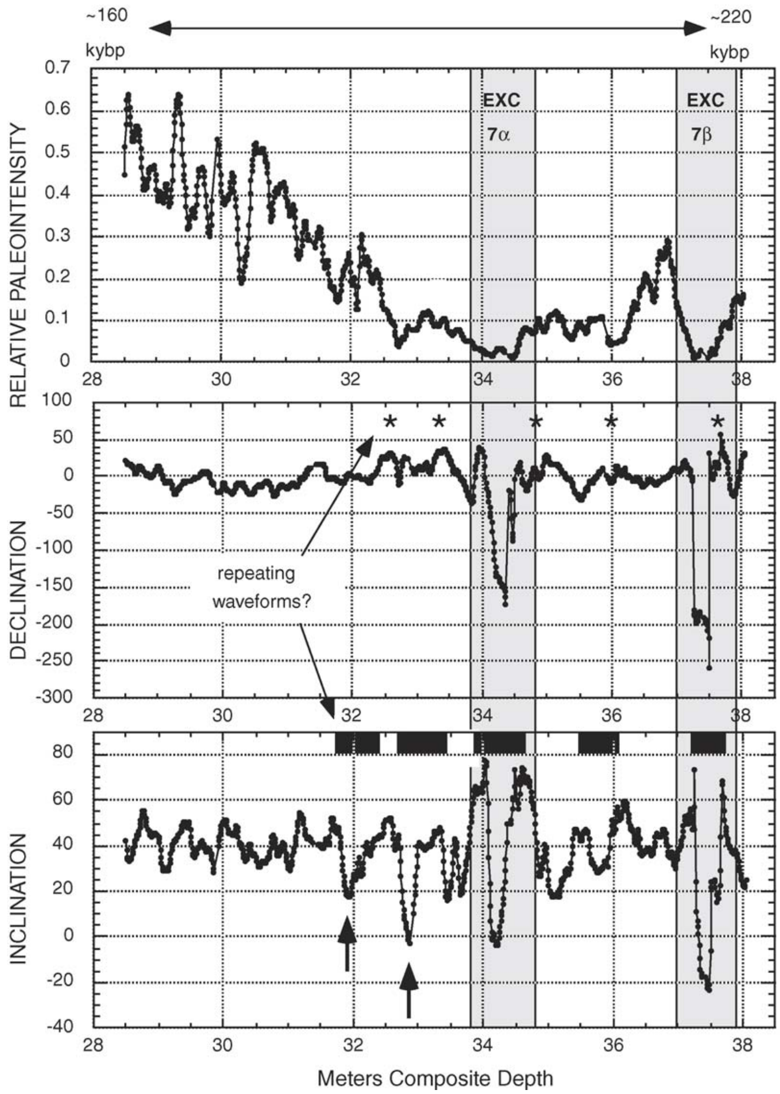

Fig. 8. Detailed paleomagnetic record of Excursions 7α and 7β from ODP Site 1061. The data come from u-channels after 20 mT a.f. demagnetization. Relative paleointensity is estimated by dividing NRM after 20 mT a.f. demagetization by u-channel magnetic susceptibility. Repeating patterns of inclination lows (indicated by black rectangles) and easterly declinations (indicated by arrows) suggest the evolution of a complex pattern of field variability (vector waveform) that is related to excursions 7α and 7β but not limited to the excursions themselves.

Roberts et al., 1997; Lehman et al., 1996; Channell, 1999), and several excursions for ODP Leg 172 (Keigwin et al., 1998; Lund et al., 1998, 2001a,b) as noted in Fig. 5. The majority of proposed excursions, however, have not been recorded within the sedimentary sections that have yielded paleointensity records.

The relationship between excursion occurrence and low paleointensity is best noted in Fig. 6 where the excursions listed in Table 1 are placed on the high-resolution Brunhes paleointensity data from ODP Sites 983/984 (Channell, 1999; Channell et al., 2004). It is clear that almost all intervals of low paleointensity during the Brunhes chron have been associated with magnetic field excursions. Similar relationships can be seen for several individual excursion records in Figs. 8 and 9. These relationships could not have been developed without paleomagnetic studies of ODP sites from around the World, and the confirmation of the older (>200 ka) excursions will only be accomplished through future paleomagnetic studies on ODP and Integrated Ocean Drilling Program (IODP) sediments due to the limited penetration of conventional piston cores.

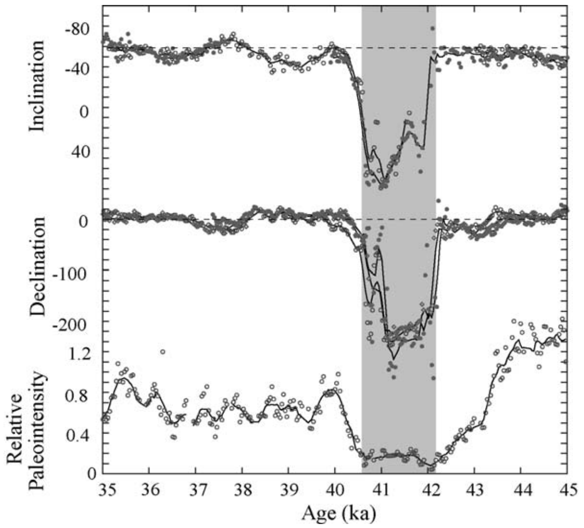

Fig. 9. Detailed paleomagnetic record of Excursion 3β (Laschamp Excursion) from ODP Site 1233. The data are overlapping sections from three different holes at Site 1233. Each record is the shipboard measurement of archive core halves after 20 mT a.f. demagnetizaiton. The relative paleointensity is estimated by dividing the NRM after 20 mT a.f. demagnetization by magnetic susceptibility. Chronology is estimated from 25 AMS radiocarbon dates (Lamy et al., 2004) as summarized by Lund et al. (2006). The excursion occurs at ∼67 mcd at Site 1233 indicting the remarkably high sediment accumulation rate at this site (∼163 cm/kyr).

5. Conclusions

The ODP has been instrumental in recovering long sequences of Brunhes-aged sediments from around the World suitable for medium to high-resolution paleomagnetic studies. These paleomagnetic studies have provided an important new view of geomagnetic field variability during a time interval of 'stable' magnetic (dipole) polarity that could not be recovered by terrestrial or deep-sea conventional piston coring. Directional PSV can be recovered from ODP sites and used regionally as a very-high-resolution chronostratigraphic tool (±200 yr resolution). ODP records of Brunhes chron relative paleointensity have dramatically improved our understanding of global geomagnetic field intensity. These records document the global-scale pattern of paleointensity and demonstrate its use as a high-resolution relative chronostratigraphic tool that under ideal conditions, in some time intervals, could have a precision of ±500 yr. ODP paleomagnetic records and associated oxygen isotope chronostratigraphies have also greatly improved our understanding of the number and ages of Brunhes excursions, and their relationship to normal directional secular variation and paleointensity variability.

Although significant progress has been made through ODP paleomagnetic studies of Brunhes-aged sediments, it is clear that more work is needed to further resolve and define the detailed global pattern of Brunhes PSV and its relationship to excursions and true polarity reversals. We have summarized a number of records that illustrate the importance of paleomagnetic studies in Brunhes ODP cores. Yet, many of the cores, noted in Fig. 1, have not had extensive paleomagnetic study. We still know remarkably little about detailed patterns of directional PSV or excursional behavior from many parts of the World where ODP cores exist but have only been subject to preliminary measurements. This paper summarizes a global perspective of Brunhes geomagnetic field behavior, but it only provides a template of ideas that require extensive testing and replication in these ODP cores in order to better quantify the true space/time pattern of field behavior and causative mechanisms for excursions during the Brunhes epoch.

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