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Long-term palaeomagnetic secular variation and excursions from the western Equatorial Pacific Ocean (MIS2-4)

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SUMMARY

New palaeomagnetic results are presented for the Pleistocene (MIS2-4) portion of deep-sea core MD98-2181 (MD81; Devao Gulf, Philippine Islands). MD81 is the highest resolution (~50 cm ky^{-1}) palaeomagnetic secular variation (PSV) record for ~12–70 ka ever recovered from equatorial latitudes (±15°). Magnetic studies indicate that MD81 has a stable natural remanence with directional uncertainties (MAD angles) typically less than 3°. We have also recovered a relative palaeointensity estimate from these sediments based on normalization to isothermal remanence. We have correlated our relative palaeointensity record with high-resolution relative palaeointensity records from the North Atlantic Ocean. The MD81 ages are always within ±500 yr of the North Atlantic records over the entire core. We also correlate our PSV record with another published PSV record from Indonesia (MD34). We are able to correlate 25 inclination features, 25 declination features and 24 relative palaeointensity features between MD81 and MD34. We identify three intervals of 'anomalous' directions in the cores (based on $>2\sigma$ deviation from mean directions). One of these intervals contains true excursional directions and is dated to ~40.5 ka. We associate this interval with the Laschamp Excursion. We also note two other intervals that have anomalous directions, but no true excursional directions. These intervals occur around ~34.5 and ~61.5 ka and we associate them with the Mono Lake Excursion (~33.5–34.5 ka) in western USA and the Norwegian-Greenland Sea Excursion (~61 ± 2 ka) in the North Atlantic Ocean. We view our 'anomalous' PSV in the three intervals to be truly anomalous even though most directions are not truly excursional. We think that it is time to reconsider the definition of what is 'anomalous' PSV or excursions. To do that we need good-quality PSV records from several regions that have reproducible records of normal PSV, excursional waveforms and relative palaeointensity. We cannot assess the difference between normal PSV and excursions without such complete PSV records. This study is one attempt to develop such a regional perspective.

Key words: Geomagnetic excursions; Palaeointensity; Palaeomagnetic secular variation.

INTRODUCTION

The character of the Earth's magnetic field behaviour between field reversals is still quite uncertain after more than 60 yr of study. We know that palaeomagnetic secular variation (PSV), the normal pattern of field variability between reversals, is punctuated irregularly with anomalous field variability, which we usually term excursions (e.g. Merrill *et al*. 1998). The space/time relationship between PSV and excursions is still uncertain and is complicated by the difficulty in determining good records of both PSV and excursions from different parts of the globe. This paper presents a new PSV record from the western Equatorial Pacific Ocean for ~12–70 ka (MIS2-4) that includes evidence for three excursions documented elsewhere, the Mono Lake Excursion (~34 ka), the Laschamp Excursion (~41 ka) and the Norwegian-Greenland Sea Excursion (~61 ka; e.g. Lund *et al*. 2006b). The special utility of this study is our ability to combine records of normal PSV, excursions and relative palaeointensity into one composite regional perspective to better consider the local relationship between excursions and normal PSV.

Our palaeomagnetic work focuses on deep-sea core MD98-2181 (referred to hereafter as MD81; 6.4°N, 125.8°E, 2114 m water depth) from the Devao Gulf, Philippine Islands (Fig. 1). The core is 3700 cm in length and covers the last ~70 ka (Stott *et al*. 2002). We have previously developed a Holocene/late Pleistocene PSV record for this core and several others from the Indonesia region (Lund *et al*. 2006a). We have also developed a preliminary relative palaeointensity record for MD81 as part of our efforts to date the entire core (Stott *et al*. 2002). This paper extends our detailed palaeomagnetic studies from ~12 to 71 ka. We develop both a directional PSV record and a final relative palaeointensity record from MD81 in this time interval. We then correlate our new results with a previously published palaeomagnetic study of core MD97-2134

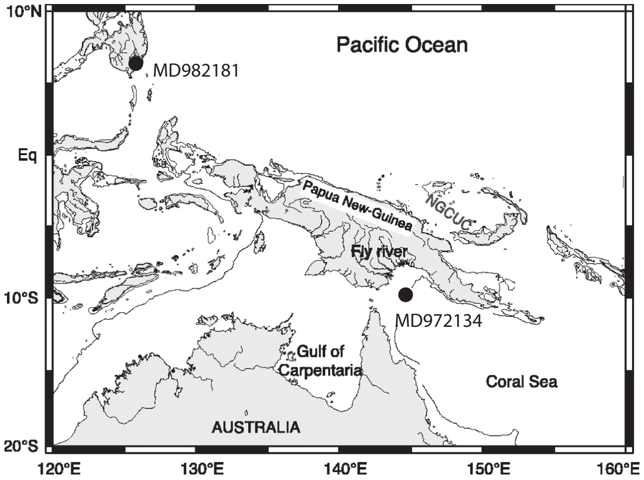

Figure 1. Map of the western Equatorial Pacific Ocean showing the location of deep-sea core MD98-2181 (MD81) in the Devao Gulf, Philippine Islands and deep-sea core MD97-2134 (MD34) from Indonesia.

(Fig. 1) from the Indonesia region (Blanchet *et al*. 2006; Leduc *et al*. 2006), which also has evidence of PSV, excursions and relative palaeointensity. Together, these two records provide a good quality, composite picture of PSV (both directions and palaeointensity) and its relationship to excursions that is unique for equatorial latitudes anywhere in the world.

Magnetic measurements

MD81 was collected by u-channel sampling the core in 1.5 m sections. The natural remanence (NRM) of all u-channels was measured and then demagnetized in alternating magnetic fields (af) and remeasured at 5, 10 and 20 mT steps. All magnetic measurements were carried out on a 2G cryogenic magnetometer at UC-Davis at 1 cm intervals. It became clear that a 3 m interval near the centre of the core contained strongly anomalous directions, which we now associate with the Laschamp Excursion. In order to more carefully analyse this interval, the 2 u-channels with the anomalous directions were cut up into contiguous 2 cm cubes for all further measurements. The cubes were remeasured at 20 mT. Then, all u-channels and cubes were af demagnetized and measured sequentially at 30, 40, 50, 60 and 80 mT. All NRM intensities were less than 5 per cent of their initial values by 80 mT.

On shipboard, MD81 had originally been measured with a long-core magnetic susceptibility system. In the laboratory, all u-channels and cubes were given an artificial anhysteretic remanence (ARM) with a 0.05 mT steady field and a 100 mT af field. The ARMs were measured and then af demagnetized and remeasured at the same steps as the NRMs. Next, another artificial isothermal remanence (SIRM) was given with a 1 T pulsed steady field. The SIRMs were measured and then af demagnetized and remeasured at the same steps as the NRMs. As with the NRMs, the SIRMs had less typically 5 per cent or less of their initial remanence after af demagnetization at 80 mT. That is what is expected for the magnetite/titanomagnetite magnetic minerals that make up the sediments (Stott *et al*. 2002; Lund *et al*. 2006b).

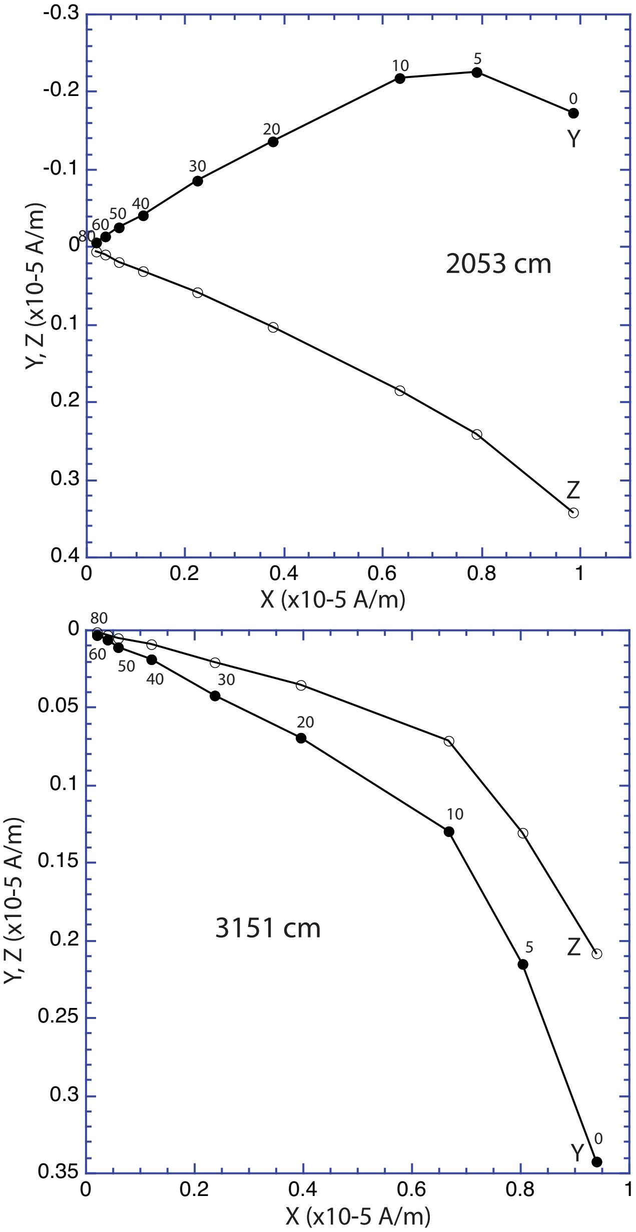

Figure 2. Alternating field (af) demagnetization of two typical samples from MD81. Solid (open) dots indicate the tip of the horizontal, *xy* (vertical, *z*) component of the natural remanence (NRM) after each demagnetization step. Numbers indicate af field in mT.

Fig. 2 shows the typical pattern of NRM directional change on af demagnetization. The NRM directions show a soft magnetic component that is largely demagnetized by 10 mT; we consider this to be a 'viscous' component acquired after coring. At 10 mT and thereafter, the NRM directions maintain a single stable direction that decays steadily toward the origin. We define a characteristic remanence (ChRM) for each sampling horizon that is the least-squares fit to directions between 10 and 60 mT af demagnetization. The sample directions that are fit to define the ChRM typically vary by less than 3° (maximum angle of deviation, MAD). (MAD values within parts of the Laschamp Excursion do vary more, probably due to low field intensity and high-frequency directional variability, but they retain a strong sense of serial correlation between successive values.)

Fig. 3 displays the pattern of NRM, ARM and SIRM intensity variation as a function of af demagnetization for the samples shown in Fig. 2. The NRM median destructive fields (MDF, where NRM is reduced by 50 per cent) are typically less than 20 mT. The ARM and SIRM MDFs are higher, but still less than 30 mT. Also, the SIRMs

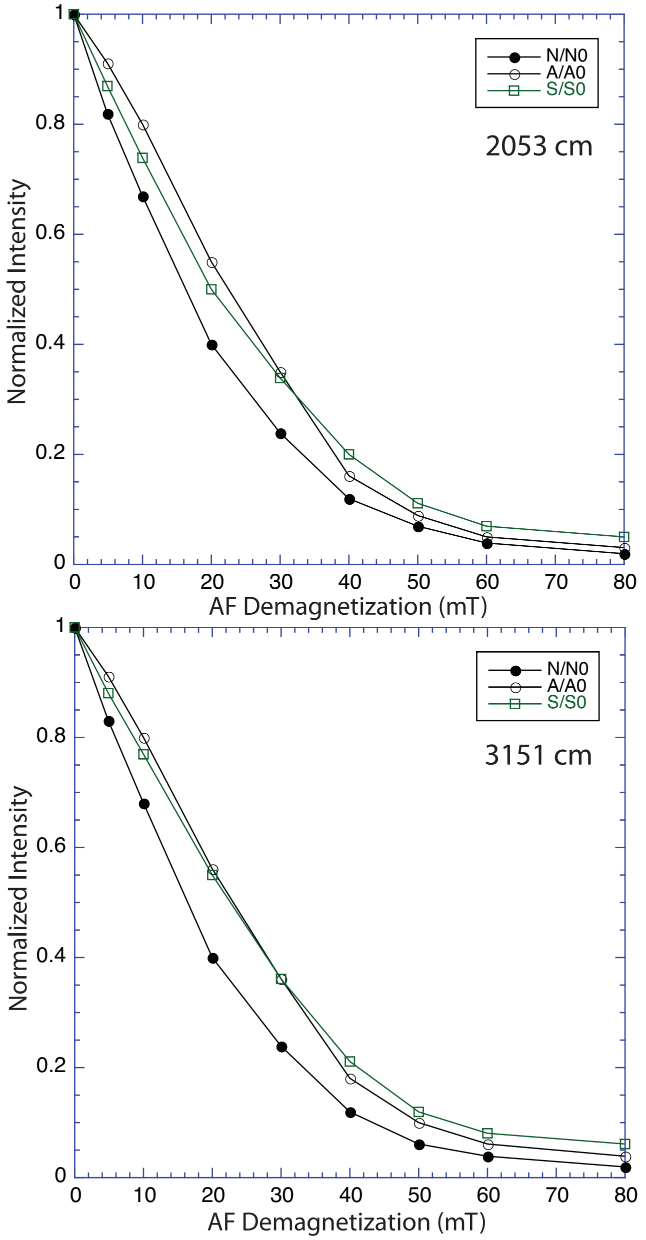

Figure 3. Relative intensity loss of the NRM (N/N0), ARM (A/A0) and SIRM (S/S0) as a function of af demagnetization.

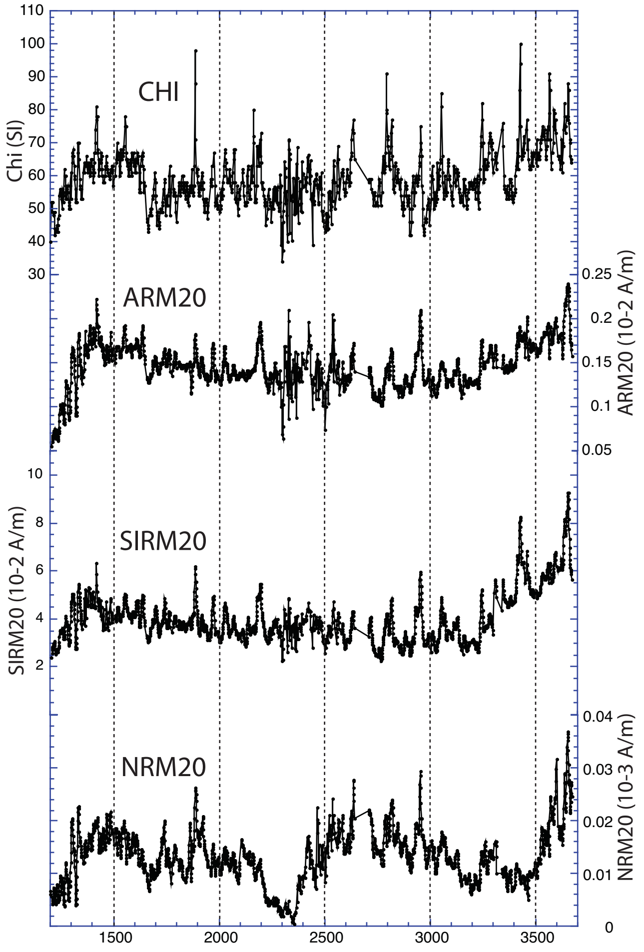

Figure 4. Chi, ARM, SIRM and NRM intensities for the Pleistocene section of MD81. The remanence intensities are all after af demagnetization at 20 mT.

are almost completely demagnetized by 80 mT. All of these values are typical for multidomain magnetite/titanomagnetite grains that are silt sized (>4 µm).

Fig. 4 displays the intensity variation of Chi, NRM, ARM and SIRM of the Pleistocene part of core MD81. All of the parameters show a quite subdued range of intensity variation with less than a factor of 3 variation over the entire stratigraphic interval. This suggests environmentally that sedimentation conditions have been generally constant from ∼12 to 70 ka. There are, however, clear centennial- to millennial-scale oscillations in intensity that relate to local palaeoceanographic variability documented by Stott *et al*. (2002) and Saikku *et al*. (2009).

The final ChRMs for the Pleistocene section of the core are plotted in Fig. 5. There is strong serial correlation between successive directions in intervals of both u-channel and discrete sample measurements and clear evidence of decimetre and longer duration directional variability. The scalar means and $\pm 2\sigma$ for the inclination and declination are plotted in Fig. 5. There are three notable intervals of inclinations and/or declinations surpassing the ±2 s limits: 2050–2100 cm in declination, 2250–2450 cm in both inclination and declination and 3400–3500 cm in both inclination and declination. We will consider these intervals below in more detail; we associate them with the Mono Lake Excursion, Laschamp Excursion and Norwegian-Greenland Sea Excursion.

We have estimated the local relative palaeointensity variation for this core by normalizing the NRM to both ARM and SIRM. For each normalizer, we have normalized the NRM after 10 and 20 mT af demagnetization to the ARM or SIRM at the same demagnetization level—NRM10/ARM10, NRM20/ARM20, NRM10/SIRM10 and NRM20/SIRM20. The ratios are all shown in Fig. 6; in all cases we have renormalized the individual ratios to their mean values (creating an average relative palaeointensity value of 1 for each ratio) in order to better compare them. It is clear that the two ARM ratios and two SIRM ratios are not significantly different from one another. Similarly, it is evident that both normalizers produce very similar patterns of overall relative palaeointensity variability. Stott *et al*. (2002) used a preliminary version of this record to correlate with relative palaeointensity records from the subtropical North Atlantic Ocean (Schwartz *et al*. 1998; Lund *et al*. 2001a,b), which

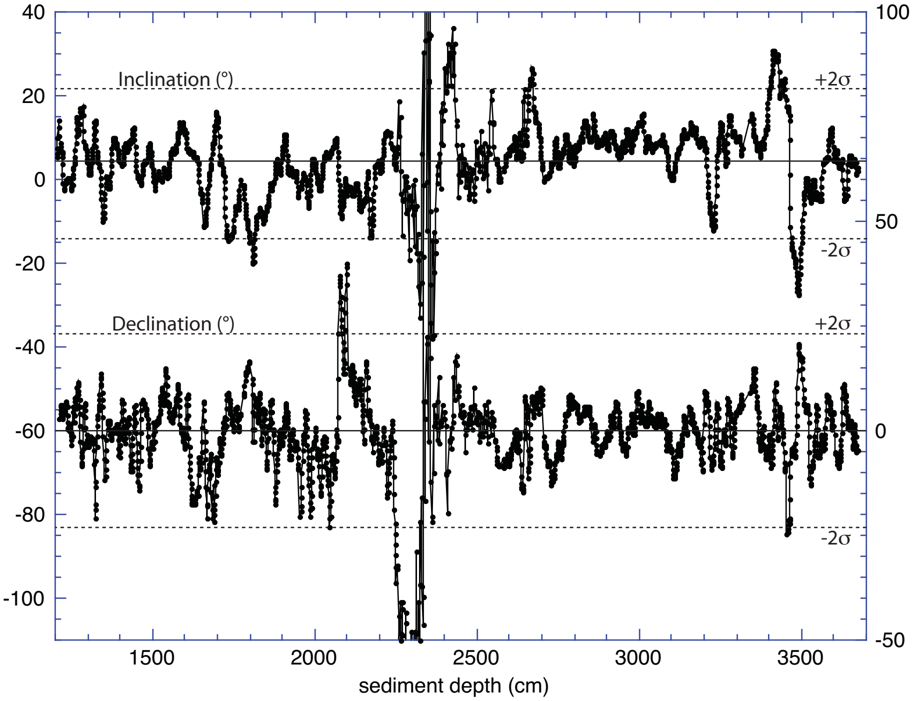

Figure 5. The ChRM directions for the Pleistocene portion of MD81. Scalar ±2σ for the inclinations and declinations is shown.

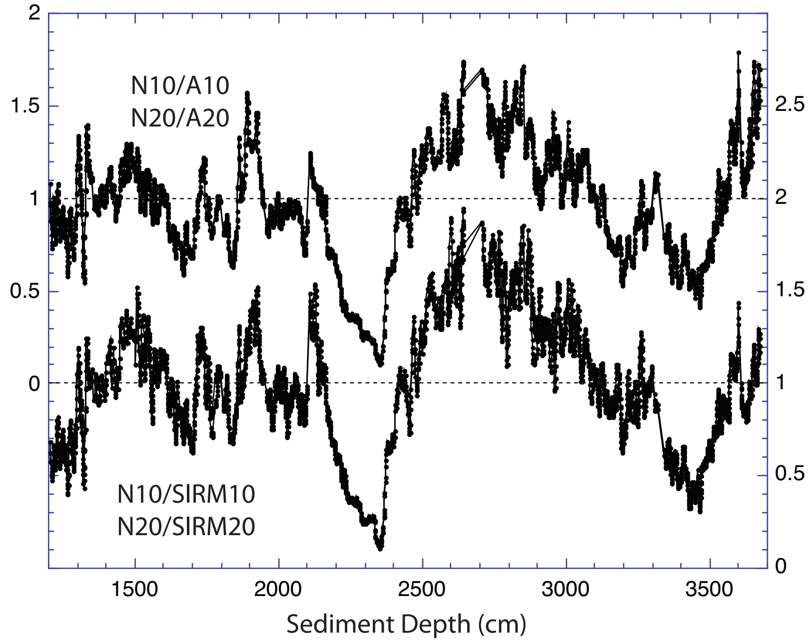

Figure 6. Relative palaeointensity estimates for MD81. We have normalized the NRM (N) by the ARM (A) and SIRM for both intensities after 10 and 20 mT af demagnetization. Each curve has been renormalized to one (dividing by the scalar mean) to make comparison of the records easier.

were dated by comparison to the GISP2 ice core record. Their correlations suggested that the two relative palaeointensity records were correlatable and synchronous with ±500 yr uncertainty.

MD81 chronology

MD81 has been dated previously with a combination of radiocarbon dating and oxygen isotope (O18) stratigraphy (Stott *et al.* 2002; Saikku *et al.* 2009; Khider *et al.* 2014). We have previously used directional PSV in MD81 to assess and intercompare radiocarbon dates over the last ∼20 ka (Lund *et al.* 2006a). As noted above, we also used preliminary relative palaeointensity in MD81 to corroborate overall core chronology (Stott *et al.* 2002).

We have drawn on these previous chronostratigraphic studies to build the chronology we use to date our new Pleistocene PSV record. We start by using the choronology of Khider *et al.* (2014) for the last 28 ka based on revised calibrated radiocarbon dating

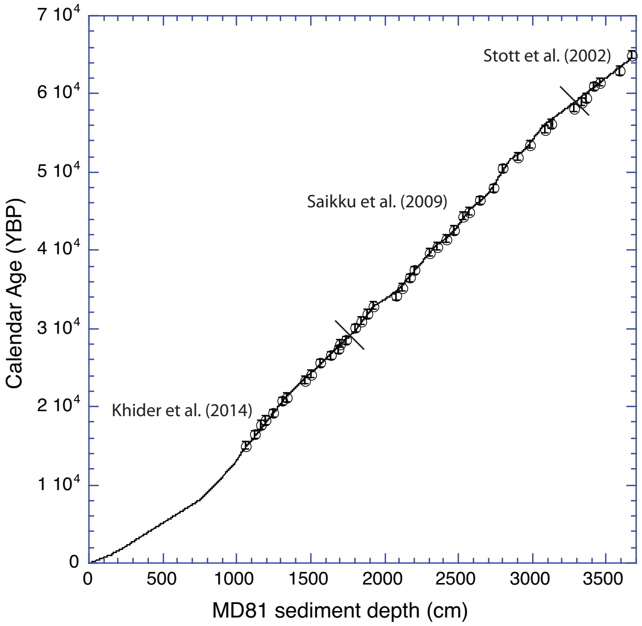

Figure 7. Chronostratigraphy of MD81. The final curve was combined from work of Saikku *et al.* (2009), Khider *et al.* (2014) and Stott *et al.* (2002). See the text for further discussion. Open circles (with ±200 yr error bars) overlay ages of selected horizons in MD81 that were dated by comparing relative palaeointensity records to other dated records (see the text for further discussion).

with more dates than were used by Stott *et al.* (2002). We use the chronology of Saikku *et al.* (2009) based on more detailed oxygen isotope stratigraphy of MIS 3 for the interval ∼30–58 ka. Finally, we use the original oxygen isotope chronology of Stott *et al.* (2002) to extend the chronostratigraphy to the core base. We have interpolated between the boundaries of these three chronological intervals to create the final composite chronology shown in Fig. 7.

We have used this chronology to date the MD81 Pleistocene PSV record. The final results are shown in Fig. 8. The relative palaeointensity records are the average of the two NRM/SIRM ratios shown in Fig. 6, with a seven-point running average. The only other directional PSV record within ∼4000 km of MD81 is another deep-sea sediment PSV record from core MD97-2134 (Blanchet *et al.* 2006). (We consider ∼4000 km to be the regional limit in which we might expect directional PSV to be correlatable [Lund 1996; Lund *et al.* 2006b].) We will compare the MD81 and MD97-2134 PSV records below. We can also compare the MD81 relative palaeointensity record with other global records (e.g. Schwartz *et al.* 1998; Channell *et al.* 2000; NAPIS-75, Laj *et al.* 2000; Lund *et al.* 2001a,b; Stoner *et al.* 2002; GLOPIS-75, Laj *et al.* 2004) under the assumption that palaeointensity variability is primarily a global phenomenon with a time resolution of ∼±500 yr. We have previously used the GISP2-based relative palaeointensity record from the North Atlantic Ocean (Schwartz *et al.* 1998; Lund *et al.* 2001a,b) to compare chronologies with lake sediment records from western North America (Benson *et al.* 2011; Lund *et al.* 2017). The North Atlantic GISP2-based relative palaeointensity record is shown in Fig. S1 in the Supporting Information. We prefer to use this regional comparison versus other published records that are stacked compilations under the presumption that we retain more detail in field variability and age control for comparison by not stacking them. We have identified more than 50 intensity features that the North Atlantic and MD81 relative palaeointensity records have in common and are consistent with the independently established composite chronologies for each region. Those features are labeled in Fig. 8 and their ages in each record are listed in Table S1 in the Supporting Information. The GISP2-based relative palaeointensity features listed in Table S1 in the Supporting Information are plotted in Fig. 7. The ages of comparable features are always within ∼±500 yr of one another over the entire extent of the MD81 Pleistocene PSV record. There is no evidence that an alternative chronology is needed to explain the correlative palaeointensity data of the two regional records. This consistency between independently dated palaeointensity records provides evidence that our MD81 chronology is reasonable. This is the same conclusion we previously reached (Stott *et al.* 2002) based on a preliminary MD81 relative palaeointensity record.

Comparison with the MD97-2134 PSV record

A full-vector PSV record was recovered from deep-sea sediment core MD97-2134 (hereafter referred to as MD34) in the Indonesia region (Fig. 1) by Blanchet *et al.* (2006). This was the first full-vector PSV record for ∼10–55 ka ever recovered from within 15° of the Equator. This record identified a number of distinctive relative palaeointensity lows and an interval of anomalous directions, which they associated with the Laschamp Excursion. The MD34 PSV record is plotted in Fig. 9. The core was dated with 13 calibrated radiocarbon dates (0–36 ka), oxygen-isotope placement of the MIS 3/4 boundary (59 ka) and assigning an age of 41 ka to the anomalous directions associated with the Laschamp Excursion (Blanchet *et al.* 2006; Leduc *et al.* 2006). The sediment accumulation rates for the core were ∼13 cm ky^{-1} from 10 to 32 ka and ∼35 cm ky^{-1} from 32 to 55 ka. (MD81, by comparison, has an average sediment accumulation rate of ∼50 cm ky^{-1} over its entire Pleistocene interval.)

MD34 is the only directional PSV record close enough to MD81 (Fig. 1; <2000 km) to merit full vector correlation. We have identified 25 inclination features, 25 declination features and 24 relative palaeointensity features that cores MD34 and MD81 have in common. Those features are numbered in Figs 8 and 9. The directional features have consistent phase relationships (inclination versus declination versus palaeointensity) as a function of time. This requirement of a consistent correlation between the two records based on three ‘independent’ parameters (inclination, declination palaeointensity) provides a unique basis for correlation that is better than correlations based on any single parameter by itself. Such a correlation also supersedes any single point of correlation based on a single parameter and the existing age chronologies of the two records. Thus, the age differences between our final PSV correlations in MD34 and MD81 almost certainly reflect problems with radiocarbon/O18 chronology rather than problems with the PSV correlations. The ages of the comparable directional PSV features (with ∼±200 yr resolution) are listed in Table S2 in the Supporting Information and plotted in Fig. 10. The two chronologies are reasonably similar to one another, but age differences between the two cores up to 1500 yr are apparent in the 32–50 ka interval. This interval is dated in MD34 only by the Laschamp Excursion (41 ka) and MIS 3/4 boundary (59 ka). We consider the MD81 chronology to be more accurate in this time interval.

Anomalous PSV

The directional PSV records from MD81 and MD34 were evaluated for their intrinsic and correlative patterns of variability. The

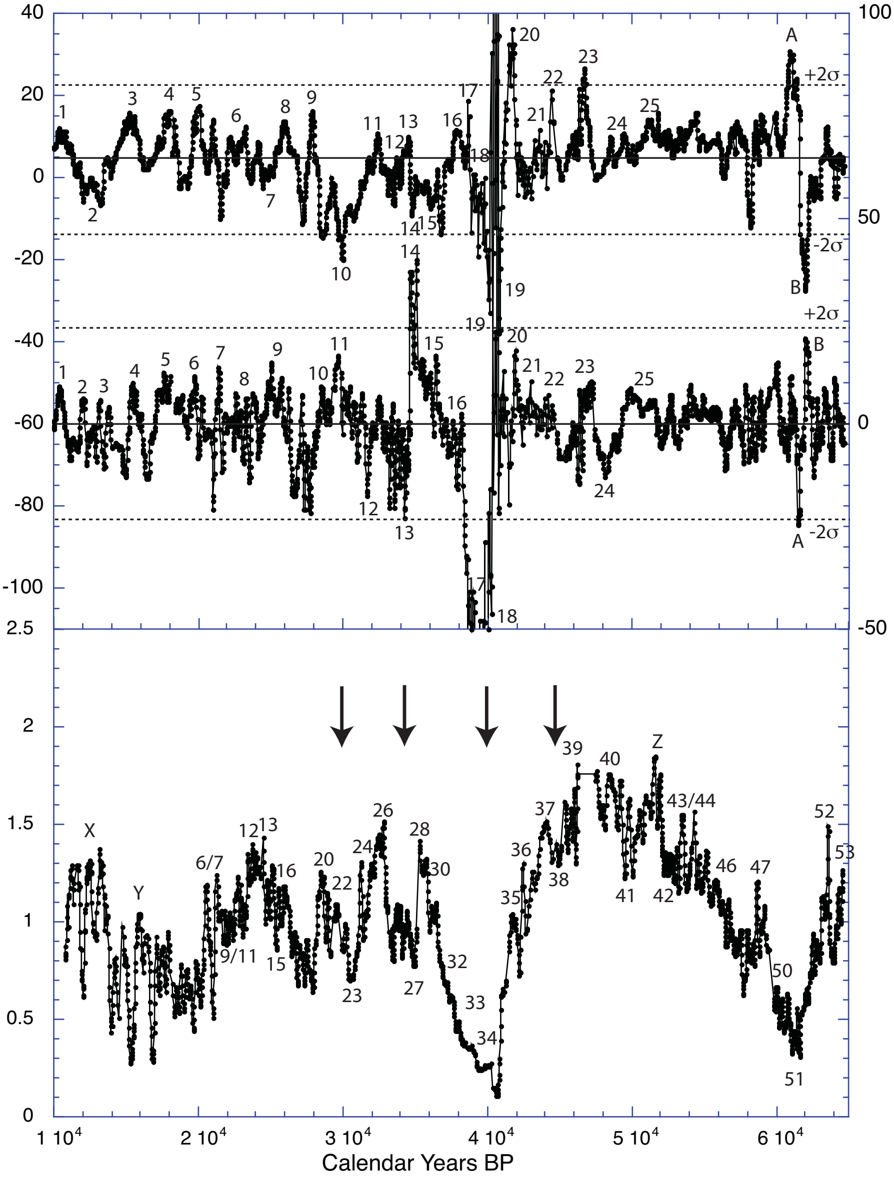

Figure 8. MD81 full-vector PSV record plotted versus time. Key inclination, declination and relative palaeointensity features that can be correlated are shown.

mean and ±2*σ* range for the scalar inclinations and declinations in both records are plotted in Figs 8 and 9. It is clear that MD81 has multiple narrow intervals in which either or both the inclination/declination values are more than 2*σ* away from their means. The most significant interval occurs at 40–42 ka in inclination and 38–41 ka in declination. The centre of this interval is ∼40.5 ± 1.5 ka. This is consistent with the interval of the Laschamp Excursion, best documented in lava flows in Europe (Bonhommet & Babkine 1967; Bonhommet & Zahringer 1969; Bonhommet 1972; Chauvin *et al.* 1989; Levi *et al.* 1990) and deep-sea sediment records from the Atlantic Ocean (Lund *et al.* 2001a,b, 2005). The Laschamp Excursion is associated with relative palaeointensity low 34 in the Atlantic sediment records and has a GISP2 age centred at 40.5 ka.

Fig. 11 shows a 'blow-up' of the Laschamp Excursion interval in MD34 (Fig. 11a) and MD81 (Fig. 11b). Key inclination, declination and relative palaeointensity features that we correlate between the two records are also shown and numbered in Fig. 11. The Laschamp Excursion interval occurs between inclination features 18–20 and declination features 18–20. The Laschamp Excursion is associated with the interval of lowest relative palaeointensity in both MD34 and MD81 records, which we correlate to relative palaeointensity feature 34 in the North Atlantic sediments. The MD81 PSV record contains true excursional directions with equivalent virtual geomagnetic poles (VGPs) associated with inclination and declination feature 19. Such VGPs are more than 45° away from the geographic North Pole (e.g. Merrill *et al.* 1998). The MD34 PSV record, however, does not contain any true excursional directions within the Laschamp Excursion interval, even though its directions are the most anomalous in the entire MD34 core. We think that the MD81 PSV record is more accurate in this interval, due to its higher sediment accumulation rate, and, therefore, we view this region to have experienced a true excursion at ∼41 ka. See also Laj *et al.* (2006) and Laj & Channell (2007) for summaries of other recent global evidence for the Laschamp Excursion.

MD81 has two other intervals of anomalous directions centred at 34.5 and 61.5 ka (Fig. 8). The first of these intervals is not

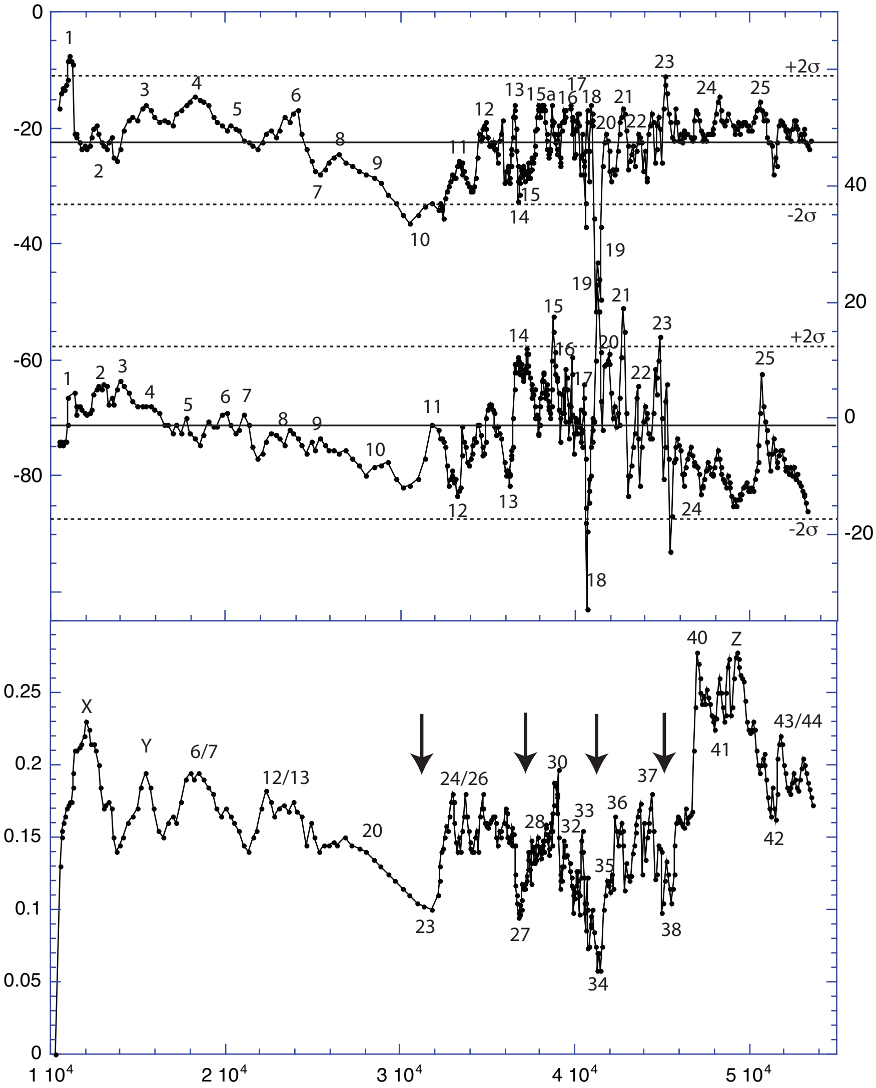

Figure 9. MD34 full-vector PSV record (Blanchet *et al*. 2006) plotted versus time. Key inclination, declination and relative palaeointensity features that can be correlated are shown.

significantly different from the Mono Lake Excursion in age. The Mono Lake Excursion was first documented in lake sediments from the western USA (Denham & Cox 1971; Liddicoat & Coe 1979; Negrini *et al*. 2014; Lund *et al*. 2017) and has been assigned an age of ∼33.5–34.5 ka. It is associated with relative palaeointensity feature 27 in deep-sea sediments of the North Atlantic Ocean, but it does not contain excursional directions in those records (Lund *et al*. 2001a,b). 'Blow-ups' of the directional PSV records from MD34 and MD81 in the Mono Lake Excursion interval are shown in Fig. 12. The interval of anomalous directions is associated with inclination features 13–14 and declination features 13–14. Neither of these records contain true excursional directions even though the declination features 13/14 are $>2\sigma$ from scalar mean values in MD81. And the accompanying inclination swing from 13 to 14 is one of the largest in either record. This pattern of anomalous directional variability is associated with the same relative palaeointensity low (27) as noted in the western USA (Lund *et al*. 2017).

The second interval of anomalous directions at ∼61.5 ka is only present in MD81 (MD34 does not extend to that time interval). Excursions near this time interval are reported from deep-sea sediment records in the high-latitude North Atlantic Ocean (Nowaczyk *et al*. 1994; Nowaczyk & Fredericks 1999). They term this excursion interval the Norwegian-Greenland Sea Excursion and date it at ∼60–70 ka. These records do not contain correlatable normal PSV, but their anomalous directions are truly excursional and appear to be correlatable on a regional scale. Dating is a complicated issue in these low-sedimentation rate (<10 cm ky^{-1}) cores, but previous summaries of Brunhes-aged excursions (e.g. Lund *et al*. 2001a, 2006a) do associate an age of ∼61 ± 2 ka with this excursion. The most significant relative palaeointensity low in the North Atlantic sediments (Fig. S1, Supporting Information) around this time (±5 ka) is feature 51 centred at 61.5 ka. Our interval of anomalous directions in MD81 is associated with inclination and declination features A–B (Fig. 8). Three of the features are truly anomalous ($>2\sigma$ from their scalar means), but, here too, the directions are not truly excursional. These anomalous directions are also associated with relative palaeointensity feature 51 at 61.5 ka.

We associate this anomalous directional interval with the Norwegian-Greenland Sea Excursion even though our data are not truly excursional. Laj & Channell (2007) and Roberts (2008) have noted, however, that some named excursions, such as the Norwegian-Greenland Sea Excursion are less well defined as to

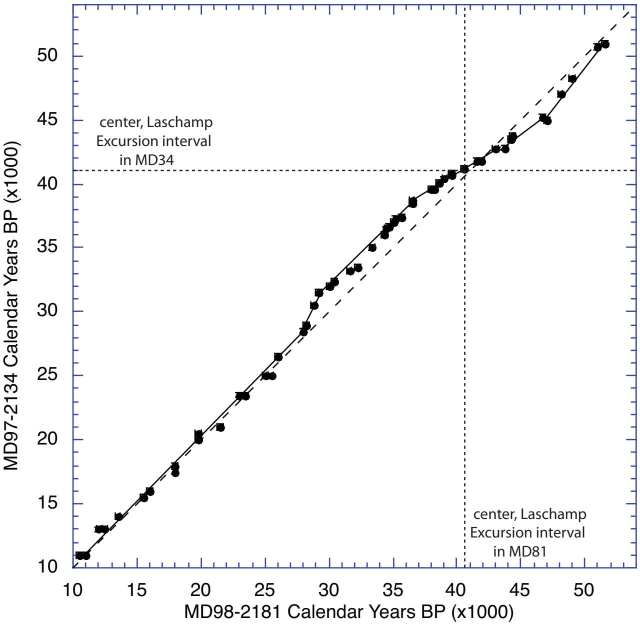

Figure 10. PSV ages of features shown in Figs 8 and 9.

data quality, true excursional behaviour, or global extent. Thus, the relationship of our record to the Norwegian-Greenland Sea Excursion should be considered tentative. The strongest comment we can make is that the interval around 61.5 ka in the west Equatorial Pacific Ocean does appear to have anomalous directional variability. This result does not corroborate the true excursional directions noted by Nowaczyk *et al*. (1994) and Nowaczyk & Fredericks (1999) or the age of their excursion. But, to the extent that the Norwegian-Greenland Sea is further verified in directional variability and timing in the future, our data put some limits on the timing and pattern of local field variability in the interval ∼55–70 ka that may relate to it.

DISCUSSION

MD81 and MD34 provide a unique view into Late Quaternary (MIS2-4) PSV at equatorial latitudes. These records provide the first full-vector view of an extended interval of PSV, which is known elsewhere to have excursional field behaviour. We see some evidence for those excursional intervals in anomalous directions in our cores. In future papers, we will consider, in more detail, the waveform and statistical character of the PSV in these cores and their relationship to excursional intervals elsewhere in the World.

The anomalous PSV directions in MD81 and MD34 do raise some more immediate and equally fundamental questions about what constitutes an excursion. Our tradition (e.g. Merrill *et al*. 1998) is that excursions ARE anomalous intervals of PSV. And that we can ‘easily’ define excursion intervals by their association with VGPs more than 45° away from the north geographic pole. However, we note evidence for ‘anomalous’ directions in both MD81 and MD34 that are not excursional by that definition. We associate anomalous directions, here, with directions more than 2σ away from their scalar mean values. We could also do the same thing by considering anomalous vector directions as those more than 2σ (α95) away from their mean vector directions. In either case, we see evidence for anomalous directional behaviour that falls outside normal expectations. One interpretation is that such directions are expected (required) statistically and have no dynamic importance. But, what makes this discussion more interesting is that the anomalous intervals always occur at times of ‘true’ excursional field behaviour elsewhere. That suggests to us that these anomalous intervals have some global-scale significance even if they do not fit the mold of true excursions. We think that it is time to reconsider the definition of what is ‘anomalous’ PSV or what are excursions, however there are currently no other high-resolution PSV records from within ±15° of the Equator during MIS2-4 to compare and aid in such an evaluation. As noted above, that evaluation of what is normal, anomalous, or excursional requires data sets that we have described here that have reproducible evidence for normal PSV that we can compare with what we think is anomalous or excursional. (An alternative point of view, which we will not consider here, is that these anomalous but not excursional intervals would be excursional if we had better quality PSV records.)

CONCLUSIONS

New palaeomagnetic results are presented for the Pleistocene (MIS2-4) portion of deep-sea core MD98-2181 (MD81; Devao Gulf, Philippine Islands). MD81 has the highest resolution (∼50 cm ky^{-1}) full-vector PSV record for ∼12–70 ka ever recovered from equatorial latitudes (±15°). Magnetic studies indicate that MD81 has a stable NRM with characteristic NRM directions that demagnetize straight toward the origin after 10 mT af demagnetization with uncertainties (MAD angles) typically less than 3°. We have also recovered a relative palaeointensity estimate from these sediments based on normalization to SIRMs.

We have correlated our relative palaeointensity record with high-resolution relative palaeointensity records from the North Atlantic Ocean (Schwartz *et al*. 1998; Lund *et al*. 2001a,b; Fig. S1, Supporting Information), which are dated by correlation to the GISP2 ice core. The MD81 ages are always within ±500 yr of the North Atlantic records over the entire core. We also correlate our PSV record with another published PSV record from Indonesia (MD34; Blanchet *et al*. 2006). We are able to correlate 25 inclination features, 25 declination features and 24 relative palaeointensity features between MD81 and MD34. This correlation between MD81 and MD34 provides the first high-resolution full-vector composite record of palaeomagnetic field behaviour from MIS 2–4 within 15° of the Equator. This is one of only a few records globally where we can directly compare intervals that contain palaeomagnetic field excursions with intervals of more normal PSV.

We identify three intervals of ‘anomalous’ directions in the cores (based on $>2\sigma$ deviation from mean directions). One of these intervals contains true excursional directions and is dated to ∼40.5 ka. We associate this interval with the Laschamp Excursion (e.g. Bonhommet & Zahringer 1969; Lund *et al*. 2005) noted elsewhere in the World. We also note two other intervals that have anomalous directions, but no true excursional directions. These intervals occur around ∼34.5 and ∼61.5 ka. These two intervals have been associated with true excursional directions elsewhere in the World: Mono Lake Excursion (∼33.5–34.5 ka) in western USA (e.g. Liddicoat & Coe 1979) and the Norwegian-Greenland Sea Excursion (∼61 ± 2 ka) in the North Atlantic Ocean (e.g. Nowaczyk *et al*. 1994).

Anomalous PSV is normally equated with excursional field behaviour and VGPs more than 45° away from the North geographic pole (e.g. Merrill *et al*. 1998). We view our ‘anomalous’ PSV in the three intervals, based on the >2 s statistical assessment, to be truly

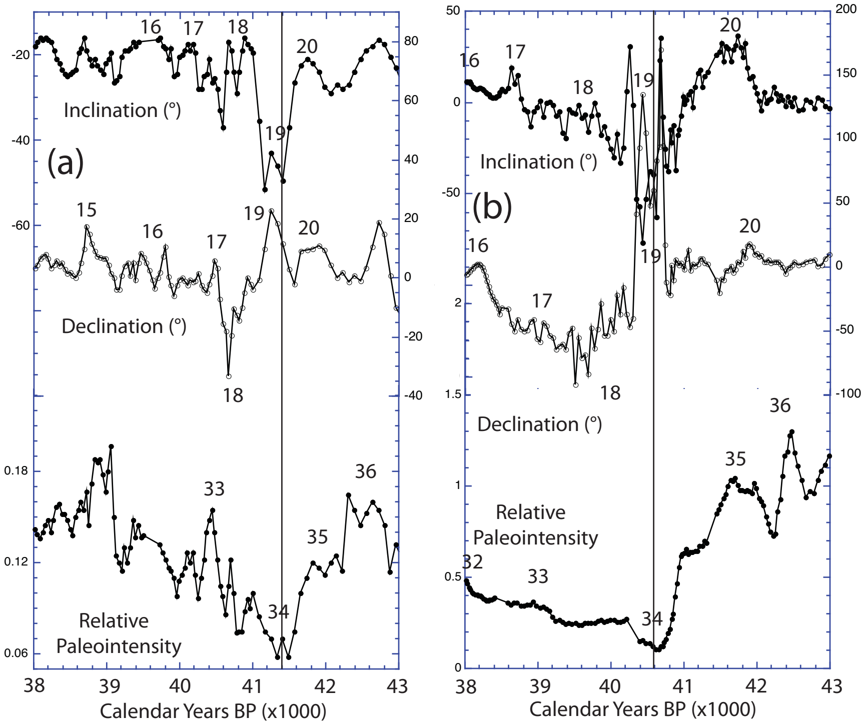

Figure 11. Blow-up of the PSV associated with the Laschamp Excursion in (b) MD81 and (a) MD34. Interval of discrete PSV measurements in MD81 extends from 38.6 to 41.6 ka.

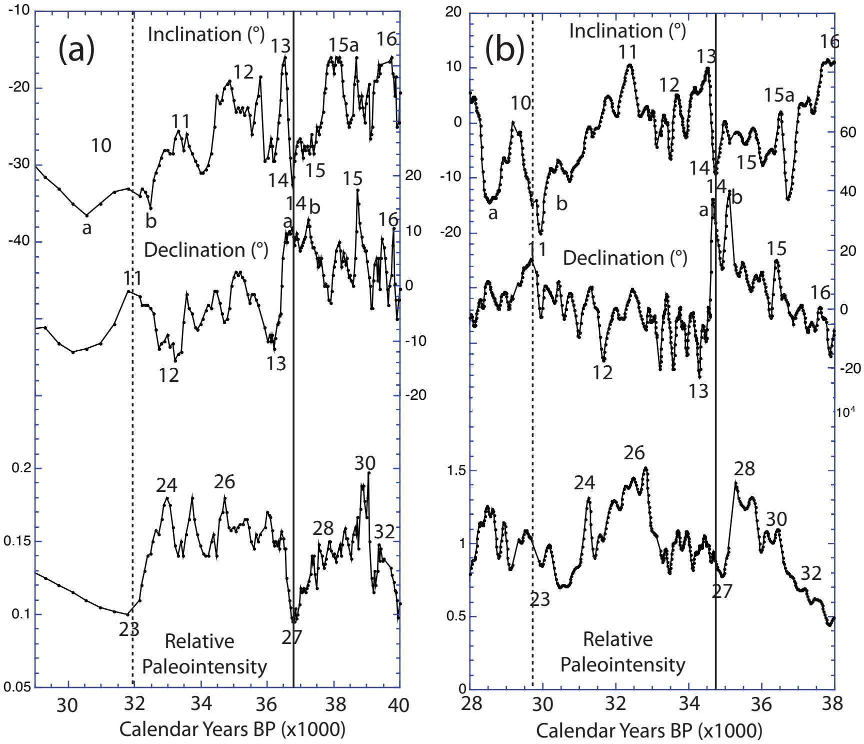

Figure 12. Blow-up of the PSV associated with the Mono Lake Excursion in (b) MD81 and (a) MD34. There are no true excursional directions in either record.

anomalous even though most directions are not truly excursional (VGPS more than 45° away from the North Pole). This suggests a more complicated space/time pattern of field variability associated with excursions than has been hypothesized before. We think that it is time to reconsider the definition of what is 'anomalous' PSV or excursional, however there are currently no other high-resolution PSV records from within ±15° of the Equator during MIS2-4 to compare and aid in such an evaluation.

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SUPPORTING INFORMATION

Supplementary data are available at *GJIRAS* online.

Figure S1. Relative palaeointensity records for three subtropical North Atlantic deep-sea records for the last 75 000 years. DO cycles 1–20 are indicated for reference.

Table S1. NATL INT correlation to MD81.

Table S2. Correlation of cores.