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High-resolution record of the Laschamp geomagnetic excursion at the Blake-Bahama Outer Ridge

Mark D. Bourne, Conall Mac Niocaill, Alex L. Thomas* and Gideon M. Henderson

Department of Earth Sciences, University of Oxford, South Parks Road, Oxford OX1 3AN, *United Kingdom. E-mail: mark.bourne@earth.ox.ac.uk*

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SUMMARY

Geomagnetic excursions are brief deviations of the geomagnetic field from behaviour expected during 'normal secular' variation. The Laschamp excursion at ∼41 ka was one such deviation. Previously published records suggest rapid changes in field direction and a concurrent substantial decrease in field intensity associated with this excursion. Accurate dating of excursions, and determination of their durations from multiple locations, is vital to our understanding of global field behaviour during these deviations. We present here high-resolution palaeomagnetic records of the Laschamp excursion obtained from two Ocean Drilling Program (ODP) Sites, 1061 and 1062 on the Blake-Bahama Outer Ridge (ODP Leg 172). High sedimentation rates (∼30–40 cm kyr^{-1}) at these locations allow determination of transitional field behaviour during the excursion. Palaeomagnetic measurements of discrete samples from four cores reveal a single excursional feature, across an interval of 30 cm, associated with a broader palaeointensity low. We determine the age and duration of the Laschamp excursion using a stratigraphy linked to the δ^{18}O record from the Greenland ice cores. This chronology dates the Laschamp excursion at the Blake Ridge to 41.3 ka. The excursion is characterized by rapid transitions (less than 200 yr) between stable normal polarity and a partially reversed polarity state. The palaeointensity record is in good agreement between the two sites, revealing two prominent minima. The first minimum is associated with the Laschamp excursion at 41 ka and the second corresponds to the Mono Lake excursion at ∼35.5 ka. We determine that the directional excursion during the Laschamp at this location was no longer than ∼400 yr, occurring within a palaeointensity minimum that lasted 2000 yr. The Laschamp excursion at this location is much shorter in duration than the Blake and Iceland Basin excursions.

Key words: Geomagnetic excursions; Palaeointensity; Reversals: process, timescale, magnetostratigraphy.

1 INTRODUCTION

Geomagnetic excursions are brief deviations in the direction and intensity of the Earth's magnetic field beyond what might be expected during 'normal' secular variation (Laj & Channell 2007). They are formally defined as short periods of time (<30 kyr) when the virtual geomagnetic pole (VGP) deviated by more than 45° from the long-term time-averaged pole position (assumed to be the geographic north pole during the Brunhes Chron) (Merrill & McFadden 1994). Estimates for the number of excursions since the start of the Brunhes Chron (∼780 ka) vary from as few as 7 (Laj & Channell 2007) to as many as 17 (Lund *et al.* 2001b, 2006), however, the number and extent of excursions is unclear (Roberts 2008) and the relationship between secular variation, geomagnetic excursions and full geomagnetic reversals remains enigmatic. Understanding and accurately constraining these observations is important for constraining geodynamo models (e.g. Wicht 2005).

Of all the excursions during the Brunhes Chron, the Laschamp excursion is the most widely recognized. The Laschamp excursion was first discovered in the Laschamp and Olby lava flows, part of the Chaîne des Puys volcanic field, central France (Bonhommet & Babkin 1967). Reversed and transitional directions in these flows, with correspondingly low field intensities, have since been dated by a number of authors (e.g. Guillou *et al.* 2004; Plenier *et al.* 2007; Singer *et al.* 2009). The most recent radioisotopic dating of the Laschamp and Olby flows using K-Ar, ^{40}Ar/^{39}Ar and ^{238}U-^{230}Th methods indicate an age for the Laschamp Excursion of 40.7 ± 0.95 ka (Singer *et al.* 2009). Lavas from the Auckland

*Now at: School of GeoSciences, Grant Institute, University of Edinburgh, Kings Buildings, West Mains Road, Edinburgh EH9 3JW, Scotland, United Kingdom.

volcanic field in New Zealand provide evidence that the Laschamp excursion was a global event (Cassata *et al.* 2008), where $^{40}Ar/^{39}Ar$ dating of lavas recording excursional directions suggests an age of 39.1 ± 4.1 ka.

While volcanic records can provide invaluable numerical ages for geomagnetic events, they are unable to continuously record high-resolution field behaviour during an excursion and accurately constrain the duration of excursions. Such continuous palaeomagnetic records can be derived, however, from marine sedimentary archives and have been important in demonstrating the global nature of the Laschamp excursion (Lund *et al.* 2001a, 2005; Channell 2006; Laj *et al.* 2006; Channell *et al.* 2012; Nowaczyk *et al.* 2012). Excursional directions have been found in marine sediments from the Irminger Basin, off the coast of Greenland (Channell 2006), to the southern Indian Ocean (Laj *et al.* 2006). Relative palaeointensity (RPI) stacks obtained from sedimentary records reveal that a significant decrease in geomagnetic palaeointensity is associated with excursional VGPs during the Laschamp excursion (Guyodo & Valet 1999; Laj *et al.* 2000, 2004; Valet *et al.* 2005; Channell *et al.* 2009). Although many of these stacks are from the Northern Hemisphere, a similar palaeointensity minimum is seen in cores from the Southern Hemisphere (Channell *et al.* 2000).

Alternative approaches may also be used to reconstruct variations in the strength of the palaeomagnetic dipole (for a full review see Roberts *et al.* 2013). Inversion of high-resolution marine magnetic anomaly records also show a minimum in palaeointensity within the Laschamp interval (Gee *et al.* 2000). However, evidence for a geomagnetic intensity minimum during this period is not confined to palaeomagnetic archives. Elsasser *et al.* (1956) demonstrated that the atmospheric production of the cosmogenic nuclide ^{10}Be is modulated by geomagnetic field intensity over millennial timescales. Since that early work, reconstructions of the geomagnetic field intensity, independent of palaeomagnetic measurements, have been derived from sedimentary ^{10}Be archives (e.g. Frank *et al.* 1997; Christl *et al.* 2003; Ménabréaz *et al.* 2011, 2012) and ice cores (Muscheler *et al.* 2004, 2005; Raisbeck *et al.* 2006). Reconstruction of the palaeomagnetic dipole for the last 200 ka using a sedimentary record of ^{10}Be production (Frank *et al.* 1997) shows a broadly similar pattern to that predicted by analysis of relative palaeomagnetic data (Ziegler *et al.* 2011). An increase in ^{10}Be production at ∼41 ka, recorded in Pacific sediments, suggests a palaeointensity minimum (Ménabréaz *et al.* 2011, 2012) coincident with the Laschamp excursion (Singer *et al.* 2009).

Duration estimates for the Laschamp excursion palaeointensity minimum, reconstructed from both ^{10}Be and palaeomagnetic records, tend to fall between 1 and 2 kyr (e.g. Laj *et al.* 2004; Lund *et al.* 2005; Ménabréaz *et al.* 2012). On the other hand, recent estimates of the duration of the directional excursion, from high-resolution sedimentary records from the Black Sea (Nowaczyk *et al.* 2012) and the Bermuda Ridge (Channell *et al.* 2012) suggest that it lasted no more than ∼500 yr. Estimates for the duration of the Laschamp excursion determined in Arctic sediments have tended to be significantly longer (Nowaczyk & Antonow 1997; Nowaczyk & Knies 2000) and, although the possibility of unusual field behaviour at high latitudes can not be completely discounted, it is likely that these 'amplified' excursion records are the result of modification of the original detrital remanent magnetization (DRM) by a self-reversed chemical remanent magnetization (CRM) (Channell & Xuan 2009; Xuan & Channell 2010).

We present here a high-resolution palaeomagnetic record of the Laschamp geomagnetic excursion from cores on the Blake-Bahama Outer Ridge in the North Atlantic Ocean. We determine the duration of the Laschamp excursion using a high-resolution stratigraphy linked to millennial-scale variation in the $\delta^{18}O$ record from the Greenland ice cores (Johnsen *et al.* 1992; Svensson *et al.* 2006, 2008). This enables us to provide an age and duration for the Laschamp excursion with greater accuracy than could be achieved using previously published age models for these Blake-Bahama Outer Ridge sites (Keigwin & Jones 1994; Grützner *et al.* 2002).

2 STUDY SITE AND SAMPLING

The Blake-Bahama Outer Ridge is a hemipelagic sediment drift located in the western North Atlantic Ocean, characterized by high sedimentation rates (∼10 s of cm kyr^{-1}). Early studies of cores from the Blake Ridge sediments identified the Laschamp interval as a palaeointensity minimum, but failed to observe excursional directions (Schwartz *et al.* 1996, 1998). Later drilling returned cores with higher sedimentation rates that recorded a directional excursion. These were then placed on an age model determined by correlating variations in carbonate content to the GISP2 ice core chronology (Keigwin & Jones 1994; Lund *et al.* 2005). The Laschamp excursion was similarly identified in sister cores from ODP Leg 172 on the Blake Ridge by shipboard palaeomagnetic measurements of half-cores (Lund *et al.* 1998; Shipboard Scientific Party 1998) and later u-channel investigations of the same cores (Lund *et al.* 2001a). Using the shipboard and u-channel palaeomagnetic measurements, we selected two sites for detailed, discrete sampling: Site 1061 (29° 58.5′N, 73° 36.0′W), located at the tip of the Blake Ridge, and Site 1062 (28° 14.8′N, 74° 25.0′W), located on the Bahama Outer Ridge approximately 210 km southwest of Site 1061 (Fig. 1). Site 1062 includes holes drilled on both the western and eastern side of a single mud wave, ∼1 km apart (Shipboard Scientific Party 1998). As the holes represent a transect across a single mud wave, they were assigned, unusually, to the same site number despite the multiple drilling locations.

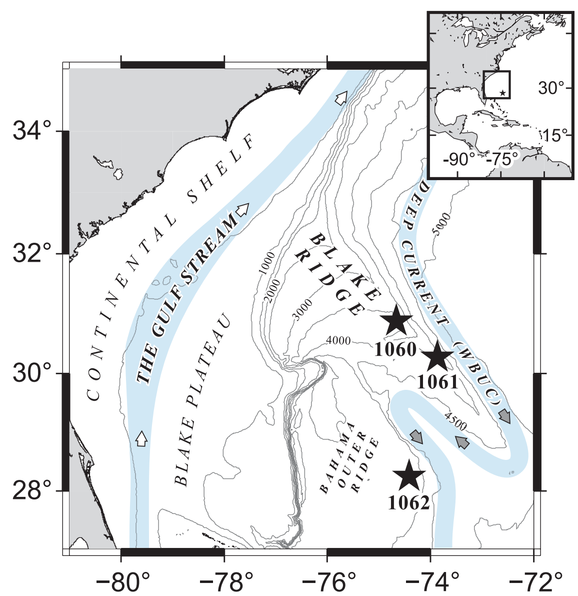

Figure 1. Location of ODP Sites 1060 (water depth: 3481 m), 1061 (4047 m) and 1062 (4772 m) on the Blake Ridge and Bahama Outer Ridge. Bathymetry data are from 'The GEBCO One Minute Grid, version 2.0, http://www.gebco.net'.

Discrete cubic samples (8 cm^3) were collected from two holes (1061B and 1061C) from Site 1061 at the IODP repository in Bremen. In all, 100 samples were taken from Hole 1061B (between 0.15 and 8.79 mbsf). Unfortunately, sampling from Hole 1061C was hindered by previous u-channel sampling in some core sections and only 21 samples were taken [between 8.90 and 13.12 m below seafloor (mbsf)]. The sampled interval from Hole 1061C does not include the directional excursion interval.

Discrete samples were also collected from three holes from Site 1062: eastern Holes 1062A, D and western Hole E. Sixty-eight samples were taken from Hole 1062D (between 4.41 and 10.01 mbsf), 47 samples from Hole 1062E (between 4.62 and 8.25 mbsf) and 47 samples from Hole 1062A (between 3.00 and 8.02 mbsf) corresponding to the intervals of interest including the Laschamp Excursion (∼41 ka). Samples were taken at varying resolution, but at the highest resolution, up to every 2 cm. Each sample effectively integrates a stratigraphic interval of 50–70 yr.

3 AGE MODEL

3.1 Composite depth scale

The ODP metres composite depth (mcd) scale for cores from Site 1061 was found to provide a good correlation between Holes 1061B and 1061C. The palaeomagnetic records from all holes from Site 1061 are subsequently given on the ODP Site 1061 mcd. The eastern holes from Site 1062, A and D, and the western Hole 1062E have different ODP mcd (Shipboard Scientific Party 1998). The 'MATCH 2.3.1' protocol of Lisiecki & Lisiecki (2002), which utilizes dynamic programming, was used to determine the best correlation between the shipboard magnetic susceptibility records from the eastern and western Site 1062 holes. The protocol compares possible alignments of the records to determine a realistic and optimal match. Using 'MATCH', the eastern hole was correlated to the western hole and a good match was achieved between the two, which was later confirmed by subsequent palaeomagnetic measurements. The palaeomagnetic records from all holes at Site 1062 are therefore given on the ODP Site 1062E (western) mcd.

It was not possible to determine an independent, high-resolution correlation between Site 1061 and 1062 using variations in carbonate content, gamma ray count or magnetic susceptibility. This reflects the different sedimentological regimes between the Blake Ridge (Site 1061) and the Bahama Outer Ridge (Site 1062). RPI proxies derived from the two sites are similar and, therefore, for the sake of comparing the two records, we present below a coarse correlation between major RPI features.

3.2 Chronology

High terrigenous sedimentation rates and carbonate dissolution at depth leaves insufficient foraminifera at Site 1061 (4047 m water depth) to readily conduct oxygen isotope analysis or ^{14}C-dating. Site 1061 cannot therefore be dated directly. Previous age models determined for Blake Ridge sites tuned variations in estimated carbonate content to orbital parameters (Keigwin & Jones 1994; Grützner *et al.* 2002). Although variations in sedimentological parameters have a first-order trend associated with glacial–interglacial cycles for some Leg 172 sites (Chaisson *et al.* 2002), their variance may be affected by local, rather than global, factors (McCave 2002). Channell *et al.* (2012) recently presented a new δ^{18}O chronology for Site 1063 (also from Leg 172) on the nearby Bermuda Rise (33° 41.2′N 57° 36.9′W). Unfortunately, it was not possible to find a suitable parameter that could be correlated from Sites 1061 and 1062 to Site 1063 at sufficiently high resolution to provide an accurate age for the Laschamp excursion.

To overcome these difficulties, we transfer an age model based on planktonic foraminifera from neighbouring Site 1060 (Vautravers *et al.* 2004; Hoogakker *et al.* 2007). Site 1060 is ∼120 km northwest of Site 1061 and is also situated on the crest of the Blake Ridge (3480 m water-depth). At a shallower water depth than Site 1061, Site 1060 is less subject to carbonate dissolution and thus an age model can be constructed for this site. To transfer the age model for Site 1060 to Site 1061, the shipboard magnetic susceptibility record of the Site 1060 ODP composite mcd splice (Shipboard Scientific Party 1998) is correlated to the magnetic susceptibility record of Hole 1061C (mcd). The 'MATCH' protocol of Lisiecki & Lisiecki (2002) was again used to determine the best correlation between the two records. The two records are similar and a match between the two was achieved (Fig. 2a).

Following the approach of Vautravers *et al.* (2004) and Hoogakker *et al.* (2007), variations in the percentage of warm planktonic foraminiferal species at Site 1060 (thought to reflect sea-surface temperatures) are correlated to δ^{18}O from the NGRIP ice core from Greenland (Andersen *et al.* 2004) using the 'MATCH' protocol (Figs 2b–d). This procedure assumes that West Atlantic sea-surface temperature and central Greenland temperature varied synchronously. For this study, ages are assigned using the GICC05 age scale for the Greenland ice cores (Andersen *et al.* 2006; Svensson *et al.* 2008) (not the older SFCP04 age scale (Shackleton *et al.* 2004) as used by Hoogakker *et al.* (2007)). However, the assigned ages are within the uncertainty of those given by Hoogakker *et al.* (2007). Our new age model for Site 1061 linked to NGRIP is compared to the previous, low-resolution age model (Grützner *et al.* 2002) for this site in Fig. 3. Within the studied interval, the age models differ by no more than 2 kyr.

4 PALAEOMAGNETIC METHODS AND RESULTS

All of the discrete samples were subjected to a 17-step alternating field (AF) demagnetization procedure. After initial measurement of the natural remanent magnetization (NRM) the samples were subjected stepwise to AFs with maximum amplitudes of 3, 6, 9, 12, 15, 20, 25, 30, 35, 40, 50, 60, 70, 80, 90 and 100 mT. All measurement and demagnetization steps were performed using a 2G Enterprises DC-SQUID cryogenic magnetometer with an in-line triaxial AF demagnetizer in a shielded room at the University of Oxford.

Representative orthogonal demagnetization diagrams from Sites 1061 and 1062 are shown in Fig. 4. Many samples have a low coercivity component that was typically removed by AF demagnetization at 20 mT. This low coercivity component was assumed to be an isothermal remanent magnetization (IRM) induced by exposure to the magnetized steel core barrel during drilling and is a common feature of material obtained by oceanic drilling (Ade-Hall & Johnson 1976; Acton *et al.* 2002).

The resulting demagnetization vectors were analysed using principal component analysis to determine the characteristic remanent magnetization (ChRM) direction for the samples (Kirschvink 1980). Removal of the drilling-induced overprint revealed a stable, single ChRM. Most samples analysed from Sites 1061 and 1062 had

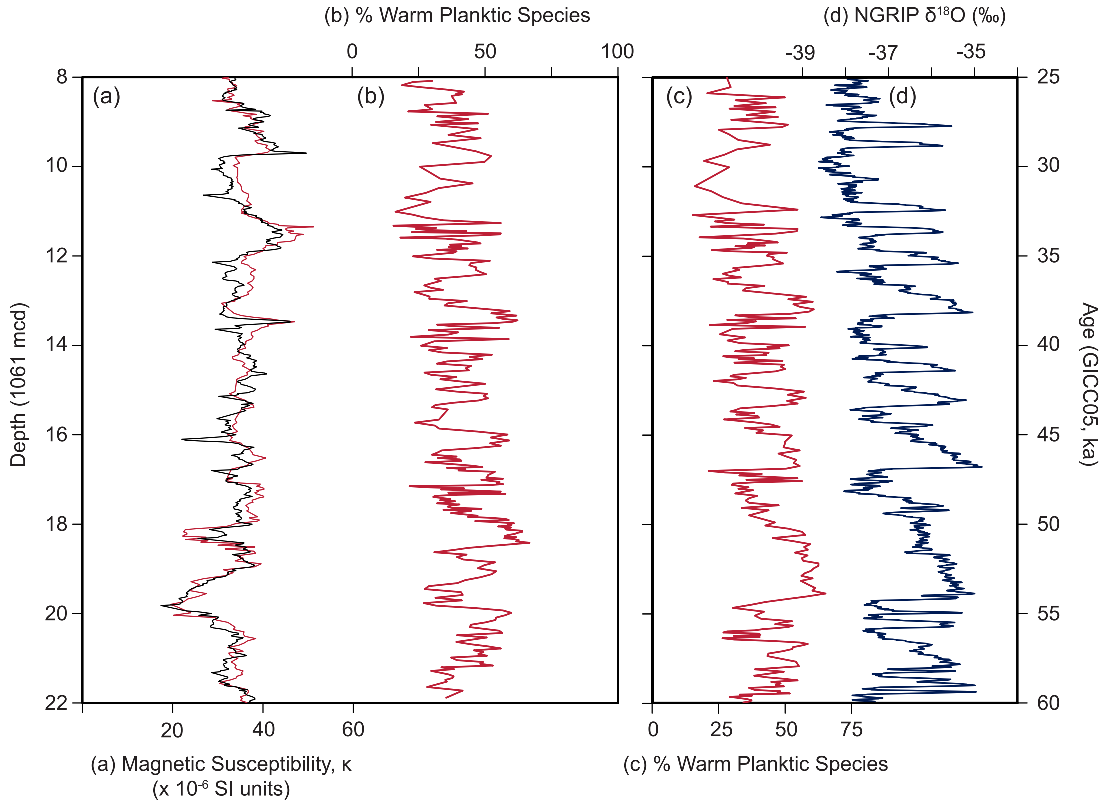

Figure 2. Site 1061 chronology: (a) correlation of shipboard magnetic susceptibility records (Shipboard Scientific Party 1998) between Sites 1060 (red) and 1061 (black) on the Site 1061 depth scale (mcd). (b) Variations in the percentage of warm planktonic foraminiferal species transferred from Site 1060 (Vautravers *et al.* 2004) onto the Site 1061 depth scale (mcd) and (c) onto the GICC05 age model (Andersen *et al.* 2006; Svensson *et al.* 2006) by correlation to (d) the NGRIP δ^{18}O record (Andersen *et al.* 2004). Correlations were achieved automatically using the 'MATCH 2.3.1' protocol of Lisiecki & Lisiecki (2002).

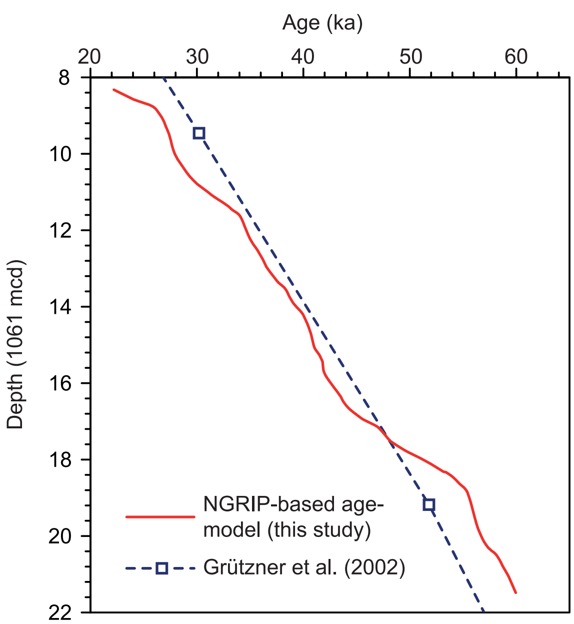

Figure 3. Age-depth models for Site 1061. Our new age-depth relationship, tied to the NGRIP GICC05 chronology (Andersen *et al.* 2006; Svensson *et al.* 2006), (red solid line) is compared to the previous, low-resolution age model for Site 1061 (Grützner *et al.* 2002) (blue dashed line).

maximum angular deviation (MAD) values less than 6°, with the majority having MAD values less than 2°. However, some samples from intervals characterized by low palaeomagnetic intensity (2–3 × 10^{-3} Am^{-1}) had MAD values greater than 6°.

4.1 Palaeomagnetic directions

Discrete sample measurements from Site 1061 and 1062 cores agree well with the expected inclination (47°) for a geocentric axial dipole (GAD) at the site latitude. As a result of the drilling process, cores were not oriented. Any measurement of declination must therefore reflect relative variations in azimuth. Progressive trends in declination along the full length of individual cores were taken as an indication that the cores twisted during extraction. To correct for this effect, we follow general practice and assume that the records conform to a GAD model, whereby the average field direction at the site (excluding excursional behaviour) is directed towards the geographic North Pole. All cores were subsequently oriented such that the mean declination outside the excursional interval is oriented towards the geographic North Pole (0°) (e.g. Knudsen *et al.* 2006; Bourne *et al.* 2012).

Hole 1061B records field behaviour during the Laschamp interval. Samples were taken every 2–3 cm, resulting in effectively continuous sampling. The major feature in the shipboard data is a substantial shallowing and slight reversal of inclination at 15.2 mcd (Fig. 5b). Two relatively broad 'shoulders' of higher than expected inclinations (up to 70°) precede and follow the excursional interval.

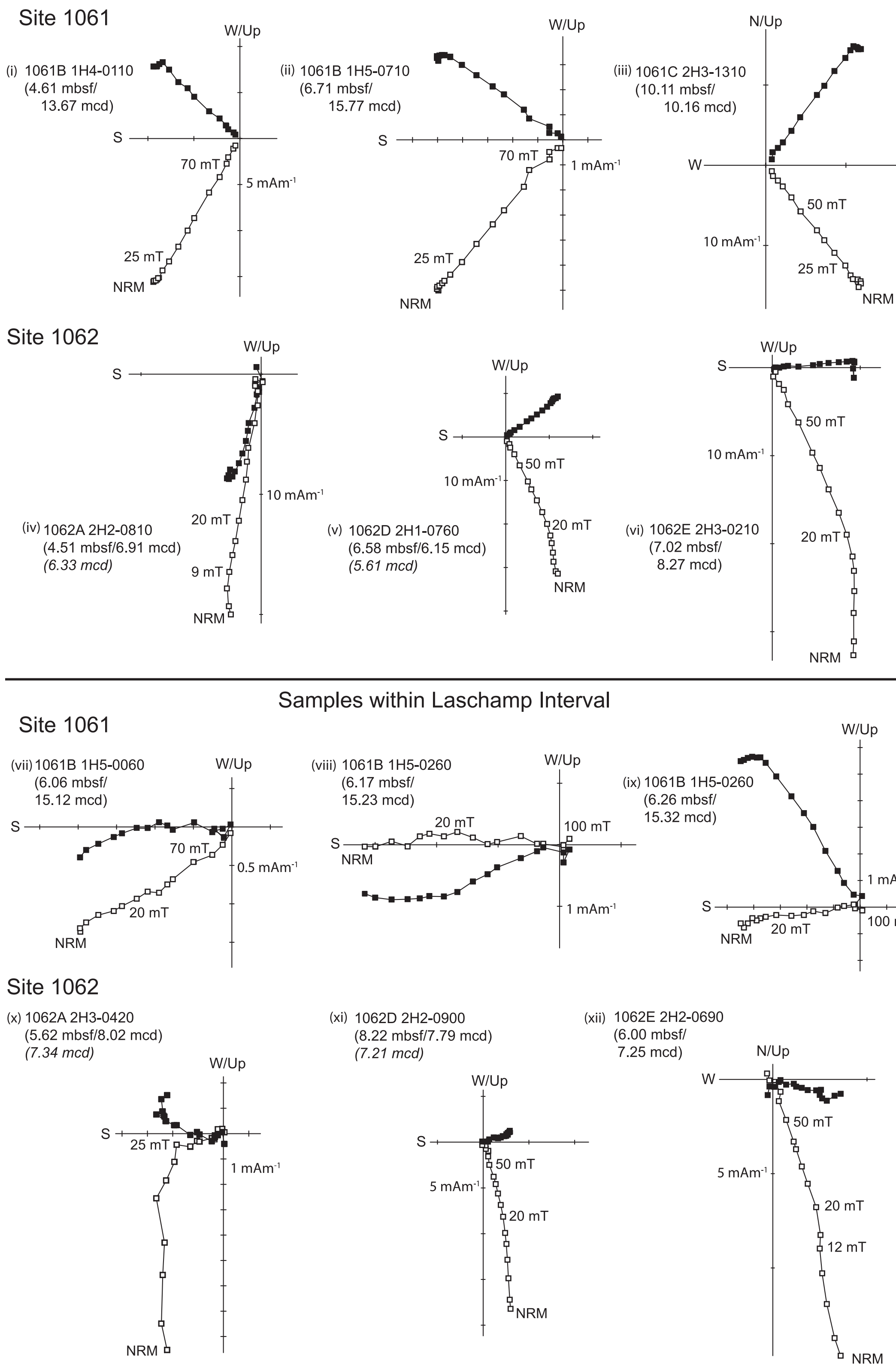

Figure 4. Representative orthogonal AF demagnetization diagrams from ODP Sites 1061 and 1062. Sample declinations are uncorrected. Magnetizations are in milli-Amperes per metre (mAm^{-1}). Open (solid) squares represent the projection of the magnetic vector onto the vertical (horizontal) plane. Italicized mcd values for samples from Holes 1062A and 1062D indicate equivalent depths in Hole 1062E. Samples (vii)–(xii) are from within the Laschamp interval. See Figs 5 and 6 for the depth position of the samples in down core plots.

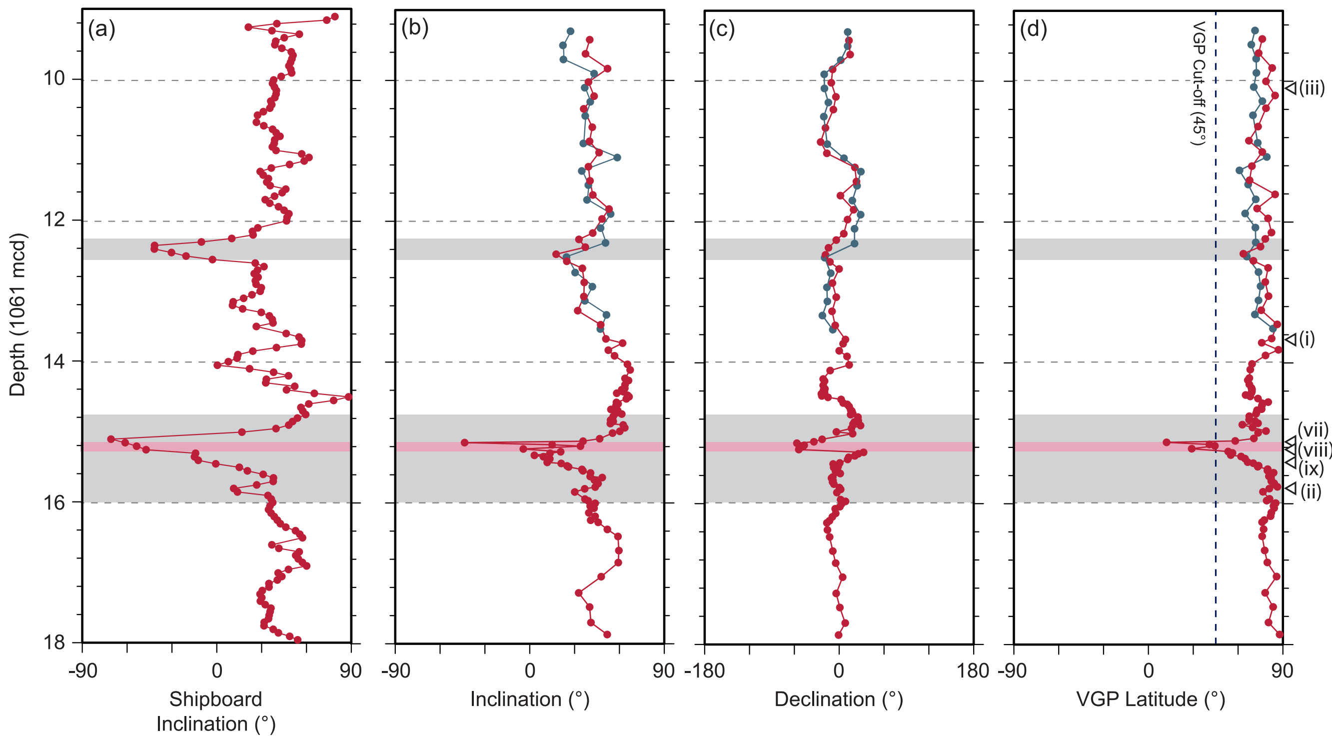

Figure 5. (a) NRM inclinations of samples from Hole 1061B measured from split-cores on-board ship (Shipboard Scientific Party 1998) and (b) ChRM inclinations for discrete samples from Holes 1061B (red) and 1061C (blue) from this study. (c) Corrected ChRM declinations for discrete samples. (d) Calculated latitude of the VGPs for all samples. The VGP cut-off co-latitude used to define the limits of the directional excursion is marked by a dashed line at 45° (pink bar) and grey shaded bars indicate low palaeointensity intervals as seen in Fig. 11. The numbered arrows indicate the depth of the representative samples from Fig. 4.

A less severe inclination shallowing also occurs at 12.4 mcd. Although the discrete samples also record two shallowing events, they fail to replicate the more steeply reversed inclinations associated with the Laschamp interval found in the shipboard measurements (−70° and −40°, respectively) (Fig. 5a). Discrepancies between the long-core and discrete sample measurements have been observed before at this site and appear to be the result of biases arising from the long-core measurement process (Roberts *et al.* 1996; Lund *et al.* 2001a; Acton *et al.* 2002; Brachfeld *et al.* 2004).

Declination records from Holes 1061B and 1061C are in good agreement with each other (Fig. 5c). Within the same interval as the inclination deviation in Hole 1061B, the declination also changes by up to 90° at ∼15.2 mcd. A second interval of similar duration at ∼14.2 mcd exhibits a second deviation towards the same direction but of lesser magnitude (∼40°).

On the basis of the shipboard inclination records from Site 1062, the shallow inclinations previously identified as the Laschamp excursion occur at ∼6.1 mcd (Fig. 6a). Our discrete sample measurements (Fig. 6b) from Site 1062 also agree well with the expected inclination for a GAD at the site but they again fail to replicate the shallower (0°) inclinations associated with the Laschamp interval in the shipboard measurements. However, there is evidence for slight but rapid deviations from the GAD direction in all three holes, 1062A, D and E, within this 20 cm interval. Between 8 and 6.5 mcd and between 6 and 5 mcd two 'shoulders' of higher than expected inclinations (up to 85°) precede and follow the excursional interval in a manner similar to that observed at Site 1061.

Declinations from Holes 1062A and D deviate within the same interval as the shallowing inclination (Fig. 6c). The records from these two cores are in good agreement with each other, with in-phase changes in declination between the cores. As at Hole 1061B, the declinations from Holes 1062A and D deviate by up to a maximum of ∼90° at 6.2 mcd. The records from Holes 1062A and D also have similar behaviour to that observed from Hole 1061B following the first deviation. The amplitude of this declination variation during the excursion is slightly different between the two cores but this may be attributable to differences in resolution.

Hole 1062E records large declination swings. The most striking features are found in sections 2H2 and 2H3 of Hole 1062E. At ∼6 and ∼7.5 mcd, positions not near core breaks, the measured declination changes by up to ∼100°. This occurs at depths not associated with the Laschamp interval and is replicated in the shipboard measurements from Hole 1062E. There are no equivalent features in Holes 1062A or D in either the continuous shipboard measurements or in our discrete measurements. Inspection of the cores does not reveal any strong evidence for physical disturbance or change in lithology. However, the absence of corroboration by the other two cores and any notable concurrent change in inclination in Hole 1062E suggests that these apparent changes in declination may have resulted from core twisting during drilling. Hole 1062E is therefore not used in further analysis of the directional behaviour of the geomagnetic field at this location.

4.2 Core properties

4.2.1 IRM acquisition

Stepwise application of an IRM can be used to determine the coercivity spectrum, and thereby the constituent magnetic mineralogy,

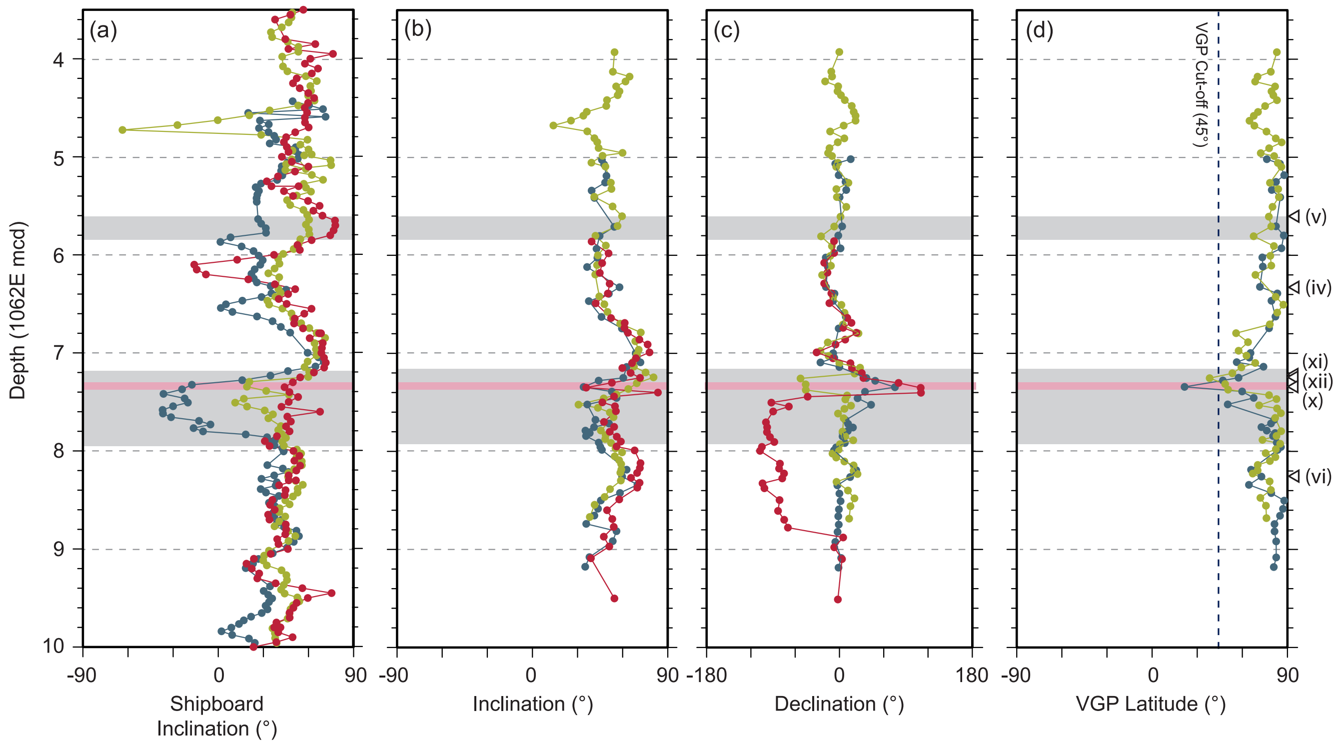

Figure 6. (a) NRM inclinations of samples from Holes 1062A (blue), 1062D (green) and 1062E (red) measured from split-cores on-board ship (Shipboard Scientific Party 1998) and (b) ChRM inclinations from discrete samples from this study. (c) Corrected ChRM declinations for discrete samples. (d) Calculated VGP latitude for all samples. The VGP cut-off co-latitude used to define the limits of the directional excursion is marked by a dashed line at 45° (pink bar). Grey shaded bars indicate low palaeointensity intervals as seen in Fig. 11. The numbered arrows indicate the depth of the representative samples from Fig. 4.

of sediments (Robertson & France 1994; Kruiver *et al.* 2001). Following complete AF-demagnetization, 32 of the samples (16 each from Holes 1061B and 1062D) were subjected to progressive forward-field IRM acquisition using a Molspin Pulse Magnetizer at the University of Oxford (Fig. 9) up to the maximum applied field of the device (800 mT). The IRM was measured between each step using the same magnetometer as for the NRM measurement. A backfield IRM was then imparted with the same fields but in the opposite direction to the initial IRM (Figs 7–10).

The S-ratio is the ratio between the SIRM and the IRM imparted in a 300 mT backfield (King & Channell 1991). It is used to indicate the relative proportions of low and high coercivity magnetic minerals. The acquisition curves were modelled using the IRM-CLG spreadsheet program (Kruiver *et al.* 2001). The curves were best modelled as two-component mixtures comprising one 'low' and one 'high' coercivity component. The modelled curves suggest that there is a 3–7 per cent contribution to the IRM from the higher-coercivity component. The majority of the samples did not appear to attain complete saturation following application of an IRM at 800 mT. However, the majority of 'S-ratios' calculated using the IRM acquired at 800 mT differ by less than 0.2 from S-ratios estimated for the modelled curves. Subsequently reported 'S-ratios' are those where the S-ratio $= -\mathrm{IRM}_{300\,\mathrm{mT}}/\mathrm{IRM}_{800\,\mathrm{mT}}$.

All the samples have an S ratio greater than 0.85, with the majority greater than 0.90 (Figs 7b and 8b). The limited variability in the S-ratio indicates that the high coercivity component contribution, and therefore the relative concentration of low-coercivity remanence carriers, varies by less than an order of magnitude (Frank & Nowaczyk 2008; Heslop 2009). The coercivity of remanence (H_{cr}), which is the backfield required to reduce a saturation IRM (SIRM) to zero, is essentially constant in both cores at $\sim 40 \pm 2$ mT (Figs 7a and 8a). The low variability of the coercivity of remanence and S-ratio with depth indicates that there has been no significant change in magnetic mineral composition within the studied time interval. It is therefore unlikely that there has been any major change in magnetic mineral provenance, a conclusion also reached by Schwartz *et al.* (1997). Detailed rock magnetic analysis of samples from Blake-Bahama Outer Ridge cores, including energy dispersive analysis and X-ray diffraction studies suggest that the principal remanence carrier within the studied interval is most likely a low-titanium titanomagnetite with potentially some degree of maghaemitization (Schwartz *et al.* 1997, 1998).

4.2.2 Magnetic susceptibility

The magnetic susceptibility depends on the concentration, grain size and mineralogy of the remanence carriers. The results of the IRM acquisition experiments demonstrate that the magnetic mineralogy of the samples does not vary through time in the studied cores. The magnetic susceptibility of the sediment can therefore be used as a proxy for the concentration of magnetic grains in the sediment. The low-field magnetic susceptibility of all samples was measured using an AGICO KLY-2 kappabridge magnetic susceptibility meter at Oxford. The mass-specific magnetic susceptibility varies by a factor of 60 per cent within the range 0.8–1.4 $\times$ 10^{-7} m^3 kg^{-1} (Figs 7c and 8c). As magnetic mineralogy is likely to have been relatively constant through time in these drift sediments (Schwartz *et al.* 1997), these fluctuations in bulk susceptibility reflect some variability in the concentration and size of the magnetic particles over 1–5 kyr timescales.

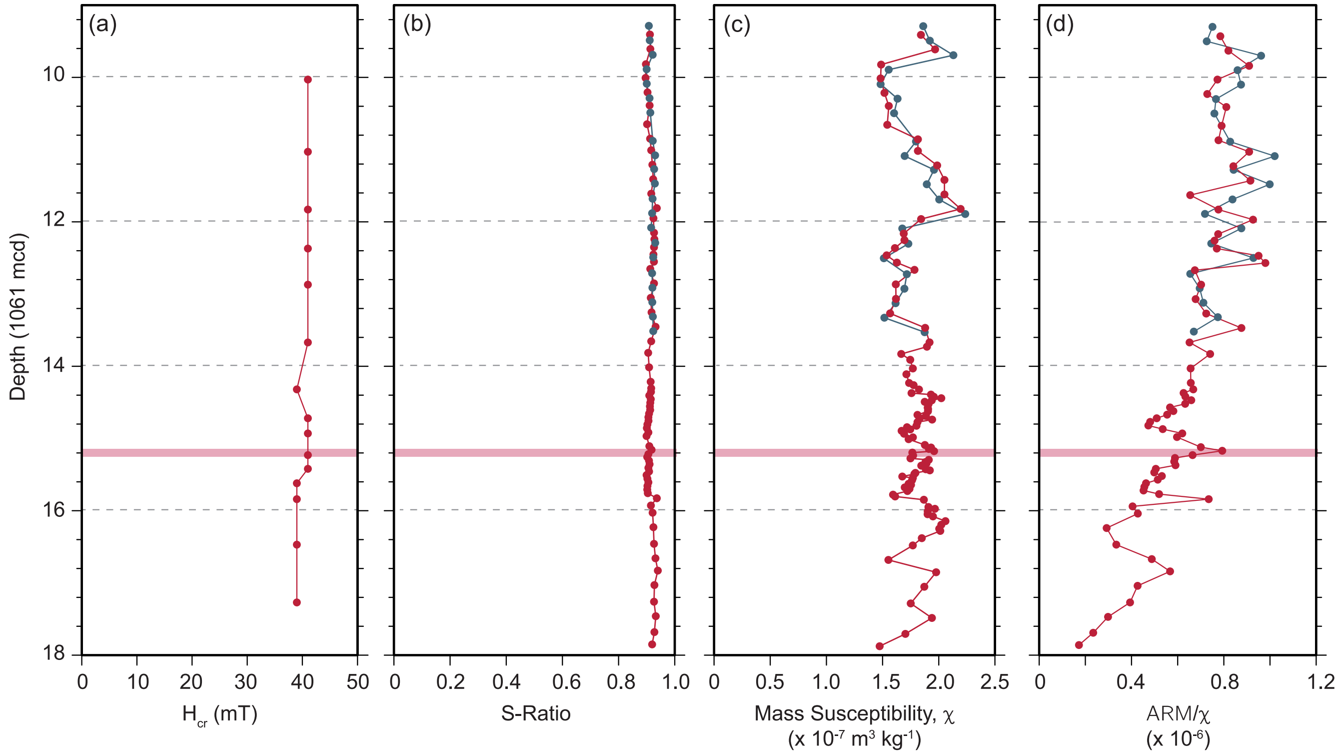

Figure 7. (a) Coercivity of remanence (H_{cr}) of measured samples from Hole 1061B. (b) S-ratio (where S-ratio=$-IRM_{0.3T}/IRM_{0.8T}$ for samples from Holes 1061B (red) and 1061C (blue). (c) Mass specific magnetic susceptibility (χ). (d) Anhysteretic magnetization divided by the measured magnetic susceptibility (ARM/χ). Directional excursion interval highlighted by pink bar defined as in Fig. 5.

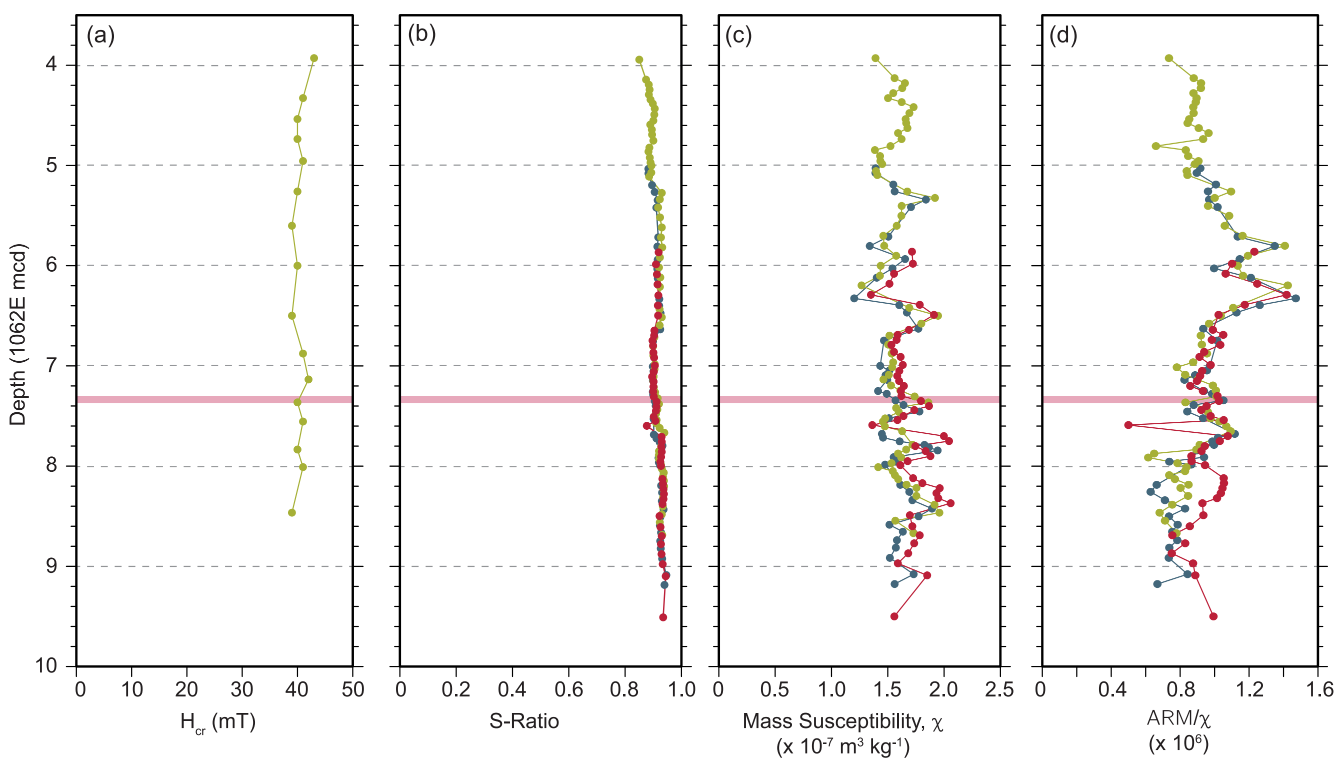

Figure 8. (a) Coercivity or remanence (H_{cr}) of measured samples in from Hole 1062D. (b) S-ratio for samples from Holes 1062A (blue), 1062D (green), and 1062E (red). (c) Mass specific magnetic susceptibility (χ). (d) Anhysteretic remanent magnetization divided by the measured magnetic susceptibility (ARM/χ). The directional excursion interval is highlighted by the pink bar as in Fig. 6.

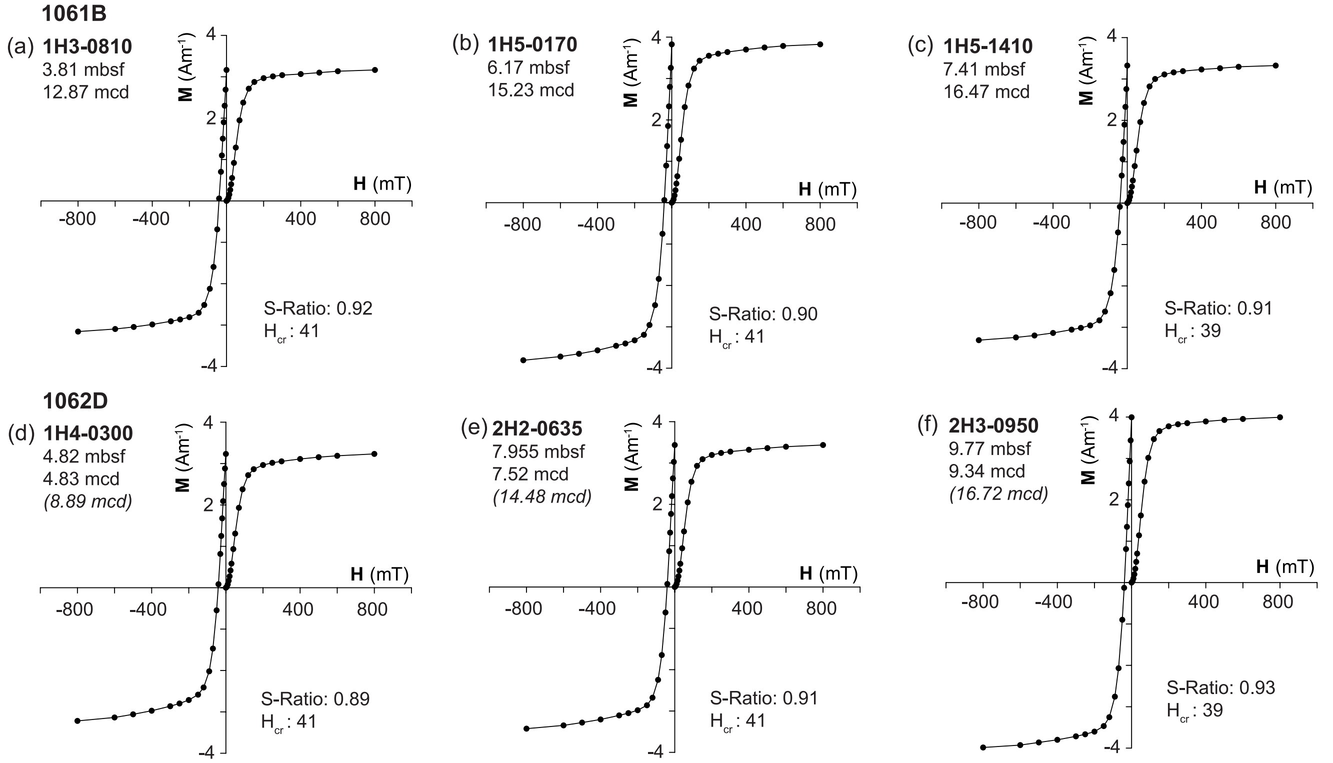

Figure 9. Examples of IRM acquisition and backfield demagnetization curves from (a–c) Holes 1061B and (d–f) 1062D. Italicized mcd depths in (d–f) indicate equivalent depths in Hole 1062E.

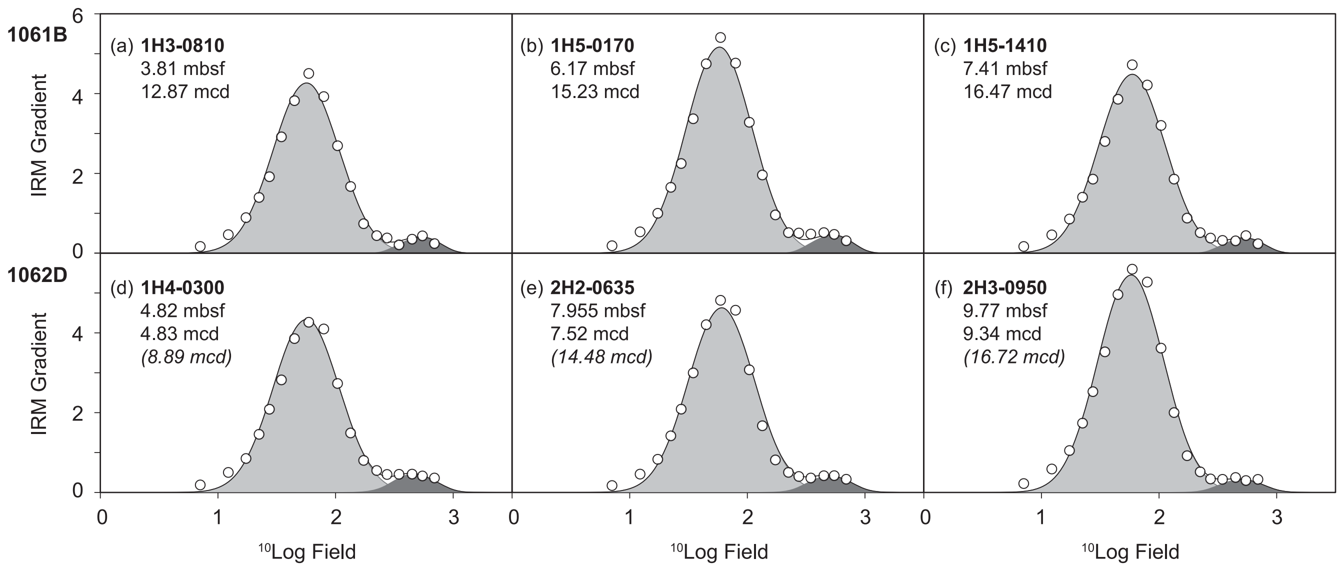

Figure 10. IRM gradient plots showing examples of modelled two-component IRM acquisition curves. The samples shown are the same as those in Fig. 9. Open symbols show the bulk IRM distribution, and the solid line represents the combined signals of the modelled 'low' (light grey shading) and 'high' (dark grey) coercivity components.

4.2.3 Grain size

The period 60–30 ka, MIS 3, is characterized by a dynamic, rapidly changing climatic system, particularly in the North Atlantic (Dansgaard *et al.* 1993; Rahmstorf 2002). The drift sediments at the Blake-Bahama Ridge are created by deposition of material by the contour-hugging Western Boundary Undercurrent (Fig. 1) (Heezen *et al.* 1966). Bulk grain-size variation studies suggest that the vigour of the bottom-water flow was significantly increased between 60 and 35 ka, with associated increased variability (Johnson *et al.* 1988; Hoogakker *et al.* 2007). It is therefore possible that magnetic grain size may also have varied throughout this interval.

The ratio of anhysteretic remanence magnetization to low-field magnetic susceptibility (ARM/χ) can be used to investigate first-order magnetic grain-size variation (Banerjee *et al.* 1981) even in situations where high-coercivity components may contribute to the magnetization (Frank & Nowaczyk 2008). The magnitude of the ARM is relatively more sensitive to the finer grain-size fraction while low-field magnetic susceptibility (χ) is particularly sensitive to the coarser grain fraction (King *et al.* 1982). Thus, an increased relative proportion of fine- to coarse-grained magnetite is indicated by higher ARM/χ ratios (King *et al.* 1983; Schwartz *et al.* 1996). An ARM was induced in the samples with a peak AF of 100 mT and a 0.1 mT direct current bias field using a DTECH-2000 AF unit at Imperial College London. The ARM was subsequently demagnetized at 20 mT.

ARM/χ for Holes 1061B and C is shown in Fig. 7(d). Hole 1061B shows a steady progression in time from lower ARM/χ values at the bottom of the record to significantly higher ARM/χ values at the top of the record. This trend indicates a decrease in the relative proportion of smaller magnetic grains through time. The ARM/χ record from Hole 1062D does not contain such a distinctive trend but between 5.5 and 6.5 mcd there is a double peak feature, suggesting two successive intervals with an increased proportion of finer magnetic grains. In both holes, the ARM/χ records are characterized by short-term variation of up to 30 per cent.

4.3 RPI proxies

Excursions are not only directional features. Constraining the palaeointensity of the geomagnetic field is important if we are to understand excursional field behaviour (e.g. Wicht & Olson 2004; Valet *et al.* 2008) and the relationship to cosmogenic nuclide production (Muscheler *et al.* 2005). Sedimentary palaeomagnetic records can only provide estimates of RPI rather than absolute field variation (Tauxe 1993; Roberts *et al.* 2013). Regardless, RPI can give important insight into the relationships between field orientation and intensity (Valet *et al.* 2005). Following Tauxe (1993), we normalize the NRM using ARM and IRM to account for changes in magnetic particle concentration. After imparting the ARM or IRM, samples were demagnetized and the remanent NRM, IRM and ARM after demagnetization at 20 mT were used to calculate the NRM/IRM and NRM/ARM palaeointensity proxies. All the records were normalized such that the maximum RPI is set equal to 1.

If changes in grain size are not accounted for by normalizing the NRM, they could adversely affect our estimate of RPI (Tauxe 1993). Previous studies of sediments from the Blake-Bahama Outer Ridge have found that, despite normalizing the NRM, up to 25 per cent of apparent low frequency palaeointensity variation may be attributable to grain size changes (Schwartz *et al.* 1996). To investigate how well environmental effects have been eliminated from our record, we calculate the squared coherence of the NRM/ARM and NRM/IRM with the grain size indicator, ARM/χ (Tauxe & Wu 1990; Tauxe 1993), using a multitaper technique (Thomson 1982; Bendat & Piersol 1986). The squared coherence between the NRM/ARM and ARM/χ, and NRM/IRM and ARM/χ, in Hole 1061B have average values of 0.64 and 0.41, respectively, indicating significant contamination of the palaeointensity record at Hole 1061B by changes in grain size. The result of this contamination may be seen in the the NRM/ARM record for Hole 1061B, where the high NRM/ARM between 16 and 18 mcd is absent from both the NRM/IRM record for Hole 1061B and from all the Site 1062 records. This feature is most likely an artefact resulting from the higher proportion of finer magnetic grains within this interval in Hole 1061B.

However, normalization of the NRM was far more successful for Hole 1062D. The squared coherence between the NRM/ARM and ARM/χ, and NRM/IRM and ARM/χ, in holes from Site 1062 have average values of less than 0.15 and 0.10, respectively, indicating that the effects of grain size variation on the Site 1062 palaeointensity records are negligible. The two RPI proxies, NRM/IRM and NRM/ARM are also in good agreement (Fig. 11). Although the two intervals with an increased proportion of finer magnetic grains at Site 1062 (between 5.5 and 6.5 mcd) coincide with an apparent RPI

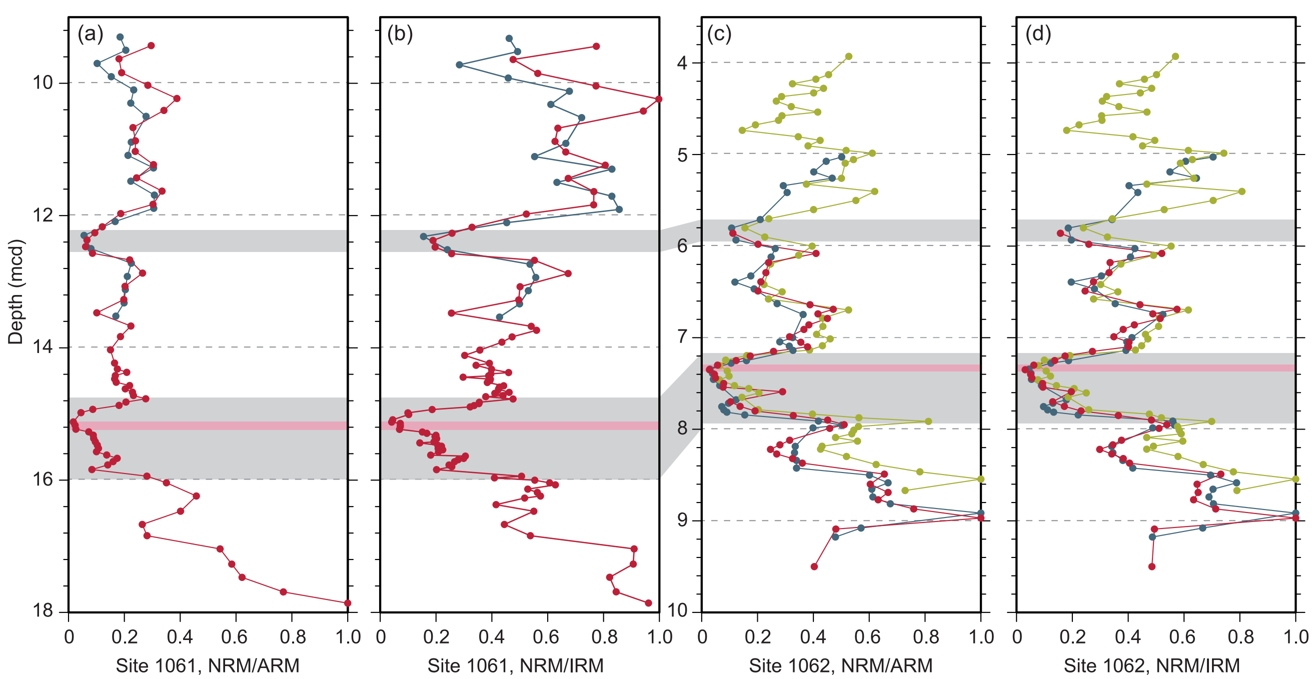

Figure 11. RPI proxies: from Holes 1061B (red) and 1061C (blue) derived by dividing the NRM by (a) the measured ARM and (b) IRM (normalized such that the maximum values for the records are equal to 1). Similarly, from Holes 1062A (blue), 1062D (green) and 1062E (red) normalized using (c) the measured ARM and (d) IRM. The grey shaded bars indicate a coarse correlation between major RPI features and the pink bars indicate the position of the directional excursion.

minimum, this RPI minimum is also seen at Site 1061 where there is no such feature in the ARM/χ record.

The impact of grain size changes on the RPI record from Hole 1061B means that this record must be treated with caution and highlights the complications resulting from environmental factors at the Blake-Bahama Outer Ridge (Schwartz *et al.* 1996). However, more confidence may be placed in the records from Site 1062. Much of the record from Site 1061 is in agreement with the more robust Site 1062 record and we employ this broad agreement to provide a coarse correlation between the two sites; Site 1061 on the Blake Ridge and Site 1062 on the Bahama Outer Ridge. Agreement between the RPI records despite the differences in sedimentological parameters, which precludes high-resolution correlation of the records, demonstrates that many of the major features in the RPI record are not primarily artefacts of sedimentological parameters.

All the records show a broad decrease in field intensity after ∼18 mcd (on the Site 1061 mcd scale), long before the directional excursion (Fig. 11). At 16 mcd, the field intensity drops relatively quickly to a broad, 1.2-m-wide minimum, at approximately one-third of the average field strength. Towards the end of this broad minimum, the field intensity drops to its lowest value, which corresponds to the main directional excursion. With the return to normal polarity, the field intensity rapidly recovers. This return to higher intensity is maintained until a second rapid drop to a minimum at 12.5 mcd. This coincides with a slight deviation in the inclination towards the equator, although this is not translated into a major deviation in VGP latitude. By 12 mcd, the field is back on a trajectory of recovery and the field intensity subsequently remains high until 9.6 mcd. This pattern is broadly similar to many observed in North Atlantic cores that span the Laschamp interval (Laj *et al.* 2000, 2004, 2006) within uncertainties in the age models (Fig. 12b) and confirms the results of previous studies of neighbouring cores (Schwartz *et al.* 1998; Lund *et al.* 2005).

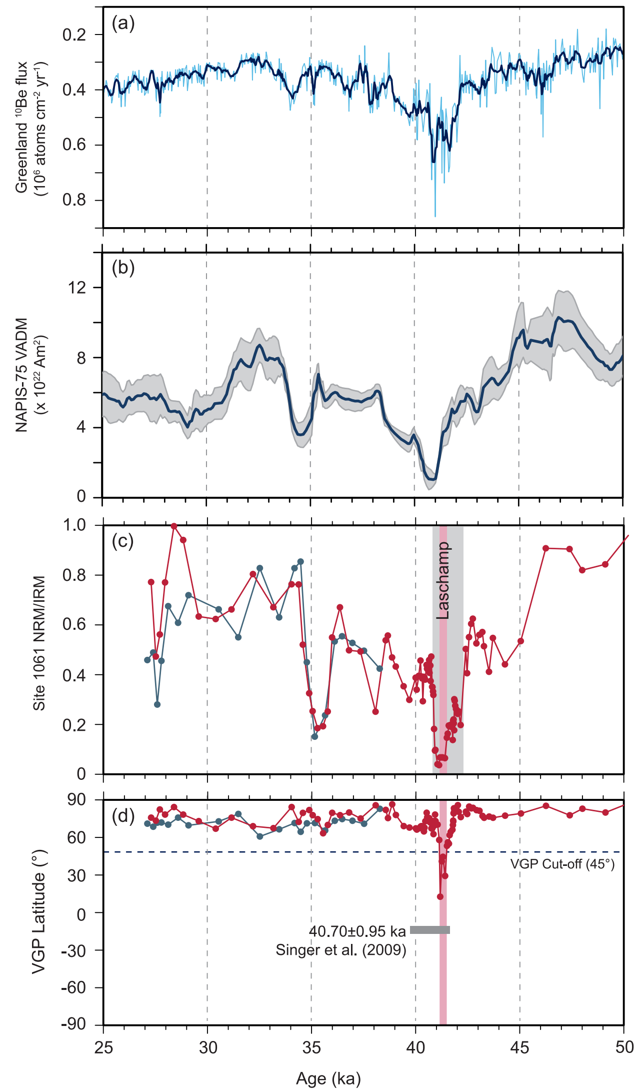

Figure 12. (a) Greenland ^{10}Be flux (Muscheler *et al.* 2004), where the darker line is a 5-point weighted average. (b) The North Atlantic palaeointensity stack (NAPIS-75) (Laj *et al.* 2000). (c) The NRM/IRM record from Site 1061. (c) The VGP latitude record of the Laschamp excursion from Site 1061 compared to the mean age of the radiometrically dated French lavas (Singer *et al.* 2009).

5 DISCUSSION

Our measurements of discrete samples provide a record of the Laschamp excursion from ODP Sites 1061 and 1062. By linking the Blake Ridge palaeomagnetic record to the NGRIP GICC05 age model (Andersen *et al.* 2006; Svensson *et al.* 2008), we can accurately constrain the timing and duration of the Laschamp excursion at the Blake Ridge.

5.1 Timing of the Laschamp excursion

To define the excursion, we assume that any deviation of the VGP beyond a co-latitude of 45° from the geographic pole represents excursional behaviour (Merrill & McFadden 1994). The record from ODP Site 1061 dates the midpoint of the Laschamp excursion at 41.3 ka, where the midpoint is taken as the halfway point in time between the start and end of the excursional deviation. This is in good agreement with the most recent numerical age for the Laschamp excursion of 40.70 ± 0.95 ka (Singer *et al.* 2009) and other recent sedimentary records of the excursion (Channell *et al.* 2012; Nowaczyk *et al.* 2012). The directional excursion to low VGP latitudes occurs at the end of the palaeointensity minimum and is associated with a sudden drop to the lowest field intensity. However, recovery of the field intensity following this directional excursion is rapid (within 1 kyr). Despite this rapid recovery, the field direction does not return entirely to its original direction, instead it maintains a slightly lower latitude (but not excursional) VGP for another few thousand years following the recovery in intensity (Fig. 12). The broad palaeointensity minimum associated with the Laschamp Excursion in the Blake Ridge record is in good agreement with atmospheric production records of the cosmogenic nuclide ^{10}Be (Muscheler *et al.* 2005) (Fig. 12).

5.2 Duration of the Laschamp excursion

The duration of the palaeointensity minimum associated with the Laschamp excursion is widely recognized as 'short' (less than 2 kyr) (Laj *et al.* 2000; Lund *et al.* 2005). The duration of the directional deviation of the Laschamp excursion has been recently estimated to be less than 500 yr (Channell *et al.* 2012; Nowaczyk *et al.* 2012). Using the 45° cut-off of the first approach, the excursion in Hole 1061B spans an interval of 0.10 m (between 15.25 and 15.15 mcd), which corresponds to a duration of 0.24 kyr (Fig. 12). Alternatively, an adaptive approach may be used to determine when the VGP deviates beyond that expected due to secular variation (Vandamme 1994). Performing this iterative calculation on the record from Hole 1061B we determine a excursional VGP co-latitude of 34.4°. Using this approach, the excursional interval in Hole 1061B spans 0.19 m (between 15.32 and 15.12 mcd), which corresponds to a longer duration of 0.44 kyr.

Directional records of the excursion at Sites 1061 and 1062 exhibit only a short deviation to low VGP latitudes, away from what might be expected during 'normal' secular deviation. Hole 1061B records VGPs that only reach a latitude of 12°, while Hole 1062A records the lowest VGP latitude of 21°. Nearby records of the Laschamp excursion from the Blake Ridge (Lund *et al.* 2005) and Site 1063 on the Bermuda Ridge (Channell *et al.* 2012), exhibit VGPs that reach high southern latitudes. Despite high sedimentation rates (>40 cm kyr^{-1}), the absence of such VGP latitudes from the record at Site 1061 implies that there has been a degree of smoothing during recording of the geomagnetic signal (Roberts & Winklhofer 2004). Each 2-cm-width sample measurement within the excursional interval represents an integrated signal of at least 50 yr. Furthermore, smoothing can arise due to a post-depositional remanent magnetization (PDRM) lock-in process. Evidence for PDRM is controversial (see, e.g. Lund & Keigwin 1994; Tauxe *et al.* 2006), however, typical estimates for lock-in depths average ∼10 cm, where up to 95 per cent of the signal could be locked in 5 cm below the surface mixed layer (Roberts & Winklhofer 2004). At a sedimentation rate of 40 cm kyr^{-1}, this would suggest that the majority of potential PDRM smoothing in this record occurs within a time-window of ∼100 yr. With this degree of smoothing, an excursion with a duration of more than 500 yr would be more clearly defined. The absence of fully reversed VGPs reinforces previous estimates of the excursional duration. Even with such a short PDRM lock-in time-scale, the record from the Blake Ridge is smoothed, indicating a short directional Laschamp excursion, close to 250 yr in duration. The directional excursion sits within a broader, ∼2 kyr palaeointensity minimum. However, within this minimum, the lowest field intensity associated with the directional excursion is also recorded over a short (∼500 yr) interval.

Previously published data from Site 1062 (Bourne *et al.* 2012) on the Bahama Outer Ridge and Site 1063 (Knudsen *et al.* 2006, 2007; Channell *et al.* 2012) on the Bermuda Ridge provide high-resolution records of other excursions. Although estimates for the duration of the directional Blake (Bourne *et al.* 2012; Channell *et al.* 2012) and Iceland Basin excursions vary (Knudsen *et al.* 2007; Channell *et al.* 2012), they all exceed the duration of the Laschamp excursion. High-resolution, discrete sample records analysed using ^{230}Th-normalization methods suggest a duration of 6.5 ± 1.3 kyr for the Blake excursion. Similarly, using ^{230}Th-normalization, Knudsen *et al.* (2007) estimated the duration of the Iceland Basin excursion to be 6.8 ± 0.5 kyr. Although estimates for the durations of these other excursions vary at these nearby locations, the duration of the Laschamp directional excursion is clearly shorter than either the Blake or the Iceland Basin excursions. Furthermore, unlike the short-duration Laschamp excursion at Site 1062, the Blake excursion at Site 1062 is characterized by fully reversed polarity VGPs that cluster around the south geographic pole for several thousand years before a rapid return to normal polarity directions (Smith & Foster 1969; Bourne *et al.* 2012). This difference in duration might support the assertion that the Laschamp represents a different category of excursion (Class I) to the Blake excursion (Class II) (Lund *et al.* 2001b).

5.3 Sensitivity to field intensity

Palaeomagnetic records have documented the existence of a later excursion, named the 'Mono-Lake' excursion, following the Laschamp excursion (Bonhommet & Zähringer 1969; Denham & Cox 1971; Liddicoat & Coe 1979). Although the record of the 'Mono-Lake' is contentious at its type locality (Zimmerman *et al.* 2006; Cox *et al.* 2012), there is clear evidence of an excursional interval following the Laschamp at a number of other locations including sedimentary records from the Irminger Basin (Channell 2006) and the Black Sea (Nowaczyk *et al.* 2012), and volcanic records from the Auckland Volcanic Field, New Zealand (Cassata *et al.* 2008; Cassidy & Hill 2009), Hawaii (Teanby *et al.* 2002) and Tenerife (Kissel *et al.* 2011). Estimates for the age of this event range from 32 (Cassata *et al.* 2008) to 34.5 ka (Nowaczyk *et al.* 2012).

According to the Blake Ridge record, a directional excursion is only apparent at the end of the RPI minimum associated with the Laschamp excursion when the field intensity drops to its lowest value. Despite high-sedimentation rates, we see no evidence for another, later, directional excursion. At ∼35.5 ka the field intensity is reduced to the same level as the RPI minimum just before the Laschamp directional excursion. Although this reduction in field intensity is commonly attributed to the 'Mono-Lake' excursion (Laj *et al.* 2000, 2004), on the chronology used in this study it is slightly older than the estimates for the Mono-Lake event at other locations. This later minimum is shorter than the Laschamp excursion minimum. Unlike the Laschamp palaeointensity minimum, the field does not then weaken further and we do not see evidence for a directional excursion at this time, merely a slight shallowing of inclination in the Hole 1061B record. It is often observed that directional behaviour of the geomagnetic field is closely linked to the field intensity (e.g. Valet & Meynadier 1993; Valet *et al.* 2005; Laj & Channell 2007). Here, we see that the directions observed are highly dependent upon the severity of the intensity drop. Despite a significant fall in palaeointensity at ∼35.5 ka, the absence of any directional excursion suggests that even this intensity decrease is insufficient to dramatically change the local field direction.

6 CONCLUSIONS

By applying a chronology linked to the NGRIP δ^{18}O record, we present a palaeomagnetic record from the Blake Ridge at ODP Sites 1061 and 1062 tied to a strong associated chronology. The Laschamp Excursion occurred at 41.3 ka, in good agreement with the most recent estimates for the age of the excursion from volcanic lava and sedimentary archives (Singer *et al.* 2009; Channell *et al.* 2012; Nowaczyk *et al.* 2012), and contemporaneous with a ^{10}Be production peak (Muscheler *et al.* 2004; Ménabréaz *et al.* 2011). Our estimate for the duration of the Laschamp directional excursion (∼250 yr) is shorter than the duration of the Blake and Iceland Basin excursions (0.9–6.8 kyr) (Bourne *et al.* 2012; Channell *et al.* 2012; Knudsen *et al.* 2007).

Unlike the Blake excursion at the same location, Sites 1061 and 1062 fail to record fully reversed polarity directions associated with the Laschamp excursion (Bourne *et al.* 2012). We attribute this to smoothing of the sedimentary record compounded by the shortness of the Laschamp excursion (e.g. Roberts & Winklhofer 2004). The difference in character of the Laschamp compared to the Blake and Iceland Basin excursions supports the assertion by Lund *et al.* (2001b) that the Laschamp excursion represents a different category of excursion that is more closely aligned with secular variation processes. We also observe that directional field behaviour is closely linked to geomagnetic field intensity. A significant global drop in field intensity, where the field intensity collapses to a minimum, is observed for all excursional directions recorded in the Blake Ridge sediments.

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SUPPORTING INFORMATION

Additional Supporting Information may be found in the online version of this article:

Table S1. Summary table of all palaeomagnetic measurements (including directional, palaeointensity and rock magnetic measurements) conducted on discrete samples from ODP Sites 1061 and 1062 in this study (http://gji.oxfordjournals.org/lookup/suppl/doi:10.1093/gji/ggt327/-/DC1)

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